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# RESEARCH MEMORANDUM

PROPERTIES OF LOW-CARBON N-155 ALLOY BAR STOCK

FROM 1200° TO 1800° F

By J. W. Freeman and A. E. White

University of Michigan

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## RESEARCH MEMORANDUM

## PROPERTIES OF LOW-CARBON N-155 ALLOY BAR STOCK

FROM 1200° TO 1800° F

By J. W. Freeman and A. E. White

## SUMMARY

The data in this report are the results of an investigation initially undertaken to establish rupture and total-deformation strengths ("design" data) at 1200° to 1800° F for typical commercial treatments of low-carbon N-155 alloy. Rupture data are reported for bar stock from two heats at 1200°, 1350°, and 1500° F and for one of the heats at 1650° and 1800° F in several conditions of prior treatment. Data on creep and on stress and time for total deformation are partially complete at 1200°, 1350°, and 1500° F.

The results show that there were large differences in strength between the heats of bar stock at temperatures above 1200° F except when a 2200° F solution treatment was used. This was due to steeper stress - rupture-time curves and lower creep resistance of one of the heats, except when they were solution-treated at 2200° F. This caused wide variation in the temperatures at which one type of treatment became superior to another. Likewise the comparison between treatments was complicated by the relationship changing depending on the criterion of strength used. Because the variation between heats indicated that the data would be of questionable value as typical design data, the work was stopped with the data on stress and time for total deformation somewhat incomplete and with very little duplication between the two heats.

The influence of prior treatment on the rupture data and design data, however, was in accordance with expectations. That is, hot-cold-work was beneficial up to a limiting temperature depending on the time period and criterion of strength used. This beneficial effect of hot-cold-work was maintained to temperatures as high as 1600° F for rupture in 1000 hours. Hot-rolled material was variable and intermediate to low in strength. Solution-treating and aging produced the highest strengths at the more elevated temperatures. The difference in properties of the two heats, however, caused wide differences in the transition temperatures of superiority of type of treatment.

The heat with the lower rupture strengths at 1350° and 1500° F developed a sigma-type phase as separate grains during testing. The reason why the sigma-type phase should be so detrimental or why it should form in one heat and not in the other is not known. There was no difference in chemical composition to account for the formation of a sigma-type phase. The only difference noted was a 1725° F finishing temperature during hot-rolling as compared with a 1910° F finishing temperature for the stock which did not develop sigma-type-phase grains. This investigation therefore indicates that hot-working conditions prior to final treatments have a pronounced effect on properties unless the final heat treatment involves a solution treatment at high temperatures to minimize variations in hot-working conditions.

## INTRODUCTION

The development and use of forged heat-resisting alloys for turbo-jet engines have been complicated by several metallurgical factors. Properties of such alloys at elevated temperatures vary depending upon the type of final treatment. As-hot-worked, aged, hot-cold-worked, solution-treated, solution-treated and aged, or solution-treated and hot-cold-worked conditions are all used in practice. The relative properties for the various types of final treatment are changed considerably by the temperatures and time periods of heat treatment, the temperatures and amount of hot-cold-work, and the treatment prior to hot-cold-work. The situation is further complicated because the relative properties vary considerably for the various conditions of prior treatment depending on the temperature, time period, and criterion of strength considered in test evaluation of the alloys or in service.

As a result, existing data for forged heat-resisting alloys are often contradictory. It is difficult to define the influence of chemical composition and practically no data exist which show consistent variations in properties for systematic changes in chemical composition. The best treatments for various service conditions are likewise not well-defined. In practical application of the alloys, strength at high temperatures is often substantially less than that predicted by test data and frequently is quite variable.

Previously an extensive study was made of the influence of type and conditions of prior treatment on the rupture properties of one heat of low-carbon N-155 alloy at 1200° F. (See reference 1.) The investigation covered by the present report initially had two objectives. One was to extend the previous investigation to include temperatures up to 1800° F. Complete evaluation of all the variations in conditions of prior treatments would have required too many tests to be practical.

Consequently it was decided to limit the testing to those conditions of prior treatment which seemed most usable in service on the basis of the results at 1200° F. Concurrently the NACA initiated a program to obtain design data in the form of curves of stress against time for total deformation at 1200°, 1350°, and 1500° F for common industrial treatments of the alloy. Again, in order to restrict the testing program to a manageable size, effort was concentrated to establish the curves for total deformations of 0.2 and 1 percent.

The available bar stock from the heat used for the tests of reference 1 was not sufficient for the entire program and it was necessary to procure more from a new heat. Duplicate rupture tests were carried out in part on both heats in order to include the two different initial materials as a variable.

The rupture tests on the second heat quickly demonstrated that there were considerable differences in the properties of the two heats except when a solution temperature of about 2200° F was used prior to testing. Apparently differences in the hot-working conditions prior to final treatment had a pronounced influence on the properties except after a high-temperature solution treatment. Recognition of this variable indicated that the design curves for the "typical" conditions of treatment would have only limited value. It also emphasized the need for concentration of effort on the fundamental crystalline structures which control properties at elevated temperatures. For this reason the testing for establishing design curves was stopped with many of the curves not too well-established.

This report presents the data obtained in the investigation with a minimum of fundamental interpretation. The main value of the results is the demonstration of the marked differences in properties at various temperatures, time periods, and criterions of strengths between two lots of stock unless they are heat-treated at high temperatures to minimize initial variations in the original test stock.

The investigation was conducted by the Engineering Research Institute of the University of Michigan under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

#### TEST MATERIAL

Low-carbon N-155 alloy bar stock from two commercial heats was used in this investigation. Chemical analyses of the two heats were as follows:

Heat	Analysis by - (1)	Chemical composition (percent)									
		C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N
30276	U.C.	0.12	1.64	0.39	21.33	18.88	18.60	3.21	1.97	1.10	0.12
	U.M.	.11	1.64	----	21.18	18.59	18.99	3.14	2.05	1.12	----
A1726	U.C.	0.13	1.63	0.42	21.22	19.00	19.70	2.90	2.61	0.84	0.13
	U.M.	.13	1.43	.34	20.73	18.92	19.65	3.05	1.98	.98	.14

<sup>1</sup>U.C. - Universal Cyclops Steel Corporation.

U.M. - University of Michigan.

The hot-working procedures used in the fabrication of the bar stock were reported by Universal Cyclops to have been as follows:

Heat 30276: The approximately 600-pound (8- by 7-inch) ingot was hammer clogged to 2-inch-square billets with 2050° F as maximum and 1750° F as minimum working temperatures. The billets were hot-rolled to 7/8-inch-square bars in one heat from 2075° F with a finishing temperature of 1725° F.

Heat A1726: The 13-inch-square ingot was hammer clogged in 15 heats to a 2-inch-square billet with 2070° F as maximum and 1730° F as minimum working temperature. The billet was hot-rolled to 7/8-inch-bröken-corner-square bars in one heat from 2110° F with a finishing temperature of 1910° F.

#### EXPERIMENTAL PROCEDURE

The bases for selecting the prior treatments to be studied were:

1. Types of treatment widely used in practice and therefore of greatest interest, or outstanding properties based on reference 1.

2. Selection of conditions of treatment were based on common practice or upon the optimum conditions indicated by the data in reference 1.

The treatments used, outlined in detail in table I, included:

1. As-rolled, as-rolled and aged, and as-rolled and hot-cold-worked because they represent common commercial practice. Other work (see reference 2) at temperatures above 1200° F had indicated that an age at 1350° F for 50 hours would be the most acceptable aging treatment. Reductions of 15 percent at 1200° F are fairly representative of commercial hot-working conditions. This hot-cold-worked condition was also included because as-rolled and hot-cold-worked material generally has adequate elongation in the rupture test at 1200° F as well as high strength.

2. Solution-treated and solution-treated plus aged materials because they are common treatments and because they were expected to have superior properties at the more elevated temperatures. Generally the higher the temperature of solution treatment the better is the strength of temperatures above 1350° F. The work of reference 1 however had indicated that for unaged material the maximum temperature of solution-treating was 2100° F without abnormally low elongation in the rupture test at 1200° F. Subsequent aging, however, improves elongation, the work of reference 1 indicating that treatment at 2200° F followed by aging at 1400° F for 24 hours gave the best combination of strength and ductility. Establishment of the design data at 1200° F on material aged for 50 hours at 1350° F was undertaken early in the program to conform with the treatments being used at other laboratories for testing at temperatures above 1200° F. (See reference 2.)

3. Solution-treated and hot-cold-worked material because this type of treatment gives by far the highest rupture strengths at temperatures on the lower end of the range being considered. The solution temperature of 2050° F was selected on the basis of the work in reference 1 which showed that 2050° F was the maximum solution temperature prior to hot-cold-work without excessive brittleness in the rupture test. A reduction of 15 percent at 1200° F was used for the reasons mentioned previously. The reduction of 25 percent was included to show the influence of increased reduction.

The room-temperature physical properties resulting from these treatments are included as table II as a matter of interest to those using the materials.

Data on stress and time for total deformation (elastic plus plastic deformation) were originally to be obtained at 1200°, 1350°, and 1500° F for all nine treatments. Sufficient tests were to be made so that curves of stress against time for rupture and for 0.2- and 1.0-percent total deformation could be plotted out to 2000 hours. Because of the excessive testing involved the program was reduced to include only

as-rolled, as-rolled plus 15-percent hot-cold-worked, 2100° F water-quenched, 2200° F water-quenched plus aged 24 hours at 1400° F, and 2050° F water-quenched plus 15-percent hot-cold-worked.

Total-deformation data were not duplicated between the two heats except at 1200° F. The evident wide difference in rupture properties between the two heats except after a 2200° F solution treatment indicated that duplicate data would have only limited utility. Furthermore, the testing program was terminated before most of the design curves were well-established.

Rupture testing was quite complete. Duplicate tests, however, between the two heats were limited to the five treatments finally selected for extensive testing. Rupture tests at 1650° and 1800° were also limited to one heat. Creep strengths reported were based on tests made to obtain design data.

Solution treatments were carried out in a gas-fired furnace. Aging was done in laboratory electric resistance furnaces. Hot-cold-working was accomplished by rolling 8-inch-long bars in a 5-inch, two high rolling mill.

Rupture tests were run in individual stationary units applying the stress through a simple-beam and knife-edge system. Rupture test specimens were 0.250 inch in diameter with a gage section 1 inch in length in all cases except the 1200° F tests on heat 30276 which were made on 0.160-inch-diameter specimens. The latter test data were taken from the previous work (reference 1). Time-elongation data were obtained during the rupture tests both by the drop-of-the-beam method and, in cases where design data were being obtained from rupture tests, by means of modified Martens' type extensometers with a sensitivity of 0.00005 inch per inch.

Creep tests were conducted on 0.505-inch-diameter specimens with a 2-inch gage length in units similar to those used for rupture testing. Duration of the creep tests varied up to 1700 hours depending on the total-deformation data needed from the particular test. The creep data were obtained by means of modified Martens' type extensometers with a sensitivity of 0.000003 inch per inch. In all cases the total deformation reported included the elastic deformation when the load was applied as well as the subsequent plastic deformation.

Room-temperature hardness, tensile, and impact tests were obtained before and after creep testing of material from heat A1726 as a measure of the structural stability of the alloy during creep testing.

Metallographic samples of the original material and the completed test specimens were prepared for observation and photomicrographs were taken of representative samples.

The indication of a sigma-type-phase formation during rupture testing was checked by X-ray diffraction methods. The procedure used was the low-angle technique outlined by Barnett and Troiano (reference 3). Rods approximately 1/16 to 1/32 inch in diameter were ground from two specimens after rupture testing. After electrolytic etching in ferric chloride to expose the sigma-phase particles, X-ray exposures of chromium K $\alpha$  radiation up to 24 hours' duration were made using a Debye-Scherrer-Hull camera. The diffraction lines obtained were compared with those reported in references 4 and 5.

The data obtained are presented as a series of tables and figures which show rupture, stress and time for total deformation, creep, and stability characteristics.

#### Rupture Test Data

The data obtained from the rupture tests are given in tables III to VII. Curves of logarithmic stress against logarithmic rupture time are shown as figures 1, 2(a), 2(b), and 2(c). The rupture strengths of table VIII were read or extrapolated from these curves. The influence of testing temperature on the rupture strength and elongation is shown by figures 3 and 4.

The relationships between properties in the rupture test and prior treatment as influenced by testing temperature were complicated. The relative properties varied depending on the time period for rupture. The two heats also had different levels of properties because the slopes of their stress - rupture-time curves were different. All of the data have been compared in figures 5, 6, 7, and 8 with those for the samples solution-treated at 2200° F and aged for 24 hours at 1400° F on the assumption that this treatment minimized differences due to initial variations in the original hot-rolled stocks.

The variation in rupture strength between the two heats was small after solution-treating at 2200° F and aging at 1400° F for 24 hours. Furthermore reference to figure 2 shows that the slopes of the stress - rupture-time curves were similar. It appeared that solution-treating at increasing temperatures from 2050° to 2200° F reduced the difference in slope between the stress - rupture-time curves which existed for the stock from the two heats in the as-rolled condition. The 2200° F solution treatment did not, however, prevent wide differences in elongation in the rupture test. In spite of the difference in elongation it appears

that the assumption of minimized variations by a 2200° F solution treatment and 1400° F age was reasonably good.

The relationship between prior treatment and testing technique was in accord with general experience. That is:

1. Above a limiting temperature the solution-treated or solution-treated and aged condition will have higher rupture strength than the hot-cold-worked condition. The temperature and degree of superiority of the hot-cold-worked condition decrease with the time period for rupture considered.

2. Solution-treated and hot-cold-worked materials have substantially higher rupture strengths for 100 and 1000 hours than solution-treated or solution-treated and aged materials up to temperatures ranging from 1450° to 1680° F. Increasing the percentage of hot-cold-work from 15 to 25 percent in the case of heat 30276 resulted in poorer maintenance of strength with both increasing time and temperature of testing.

3. The strengths of stock hot-cold-worked in the as-rolled condition are not maintained as well as those solution-treated prior to hot-cold-work when testing time or temperature is increased.

4. Strengths in the hot-worked condition also tend to fall off rapidly in comparison with those of solution-treated stock with increasing time or temperature for rupture and are particularly low at temperatures above 1350° to 1500° F.

5. General experience indicates that comparative rupture strength increases with solution temperature as the test temperature or time is increased. This effect was only minor in the case of heat 30276. The data suggest it would have been even less for heat A1726.

6. The influence of aging after solution treatment on the rupture strength at varying temperatures is not well-defined by the data. At 1200° F aging for 24 hours raised the level of the stress - rupture-time curves. There was practically no effect at 1350° F. At 1500° and 1650° F the short-time strengths were increased somewhat by aging and the long-time strengths lowered because of steeper stress - rupture-time curves after aging. At 1800° F there was no significant effect.

Aging of hot-worked material seems too complicated to define in view of the differences in hot-worked materials. In the case of heat 30276 aging at 1350° F for 24 hours had little effect at 1200° and 1500° F while it reduced the slope of the stress - rupture-time curve at 1350° F. Considerably different effects would probably have been obtained by aging the as-rolled stock from heat A1726.

7. The elongation data from the rupture tests showed that abnormally low elongation only results during testing at 1200° F. While differences exist at higher temperatures all elongations were at least 5 percent. Solution-treating or hot-cold-working resulted in elongation below 5 percent at 1200° F. The samples without hot-cold-work tended to reach a maximum in elongation at 1350° to 1500° F, whereas the hot-cold-worked materials tended to have increased elongation with increasing temperature of test. Consequently the hot-cold-worked conditions had higher elongation at the higher temperatures.

When the investigation was undertaken it was hoped that the temperatures of superiority of rupture strength for the various treatments would be defined. The results, however, show the optimum properties at intermediate temperatures vary depending on the response of the particular lot of bar stock to the treatment as well as the time period on which comparisons are based. At 1200° F the best properties were obtained by hot-cold-work in all cases. Solution-treated or solution-treated and aged was best at 1800° F. The temperature at which the change-over occurred varied widely for the two heats and the various prior treatments. The temperatures at which the material solution-treated at 2200° F and aged at 1400° F became superior to other conditions have been compiled in table IX to illustrate this finding.

#### Characteristics of Stress and Time for Total Deformation

Design curves showing the relationship between stress and time for various total deformations are shown in figures 9 to 15. The data for these curves were taken from time-elongation curves from the individual tests, as summarized in tables X to XIII.

Stresses for total deformations of 0.1-, 0.2-, 0.5-, and 1.0-percent total deformation and the transition to third-stage creep in 10, 100, 1000, and 2000 hours as defined by the design curves are summarized in tables XIV and XV. In a number of cases the data were not sufficiently complete at the time testing was terminated to define all the deformation strengths. The influence of prior treatment on the various deformation strengths at the three temperatures at which heat A1726 was tested is shown graphically by figure 16. The curves of stress and time for total deformation at 0.2- and 1.0-percent deformation for the various treatments are compared in figures 17 and 18.

The results of the total-deformation tests indicate that:

1. Hot-cold-work substantially increases the permissible stress for limited total deformations for time periods up to at least 2000 hours at 1200° and 1350° F but not at 1500° F.

2. As in the rupture tests the as-rolled stock from heat A1726 compared favorably with the solution-treated and the solution-treated plus aged conditions. In this condition heat 30276 was inferior at 1200° F, the only temperature at which it was tested.

3. There was only a small difference between material solution-treated at 2200° F and material solution-treated at 2200° F and aged for 24 hours at 1400° F.

4. Total-deformation data are a complex combination of initial deformation when the load is applied, the amount of first-stage creep, and the inherent creep resistance. The first two are more influential at the lower temperatures and higher total deformations considered. Differences due to prior treatment tend to become less as the amount of total deformation decreases. Creep resistance would have more influence at longer time periods than those considered in the investigation. Two cases where low creep resistance probably contributed to low comparative total-deformation strength were the material from heat 30276 in the hot-rolled condition and in the solution-treated plus hot-cold-worked 25-percent condition.

5. The wide difference in the two hot-rolled materials at 1200° F probably indicates that there would have been wide differences in the total-deformation characteristics if the two had been tested with other treatments. As in the rupture test this difference probably would have been a minimum after a 2200° F solution treatment. Except for the solution-treated and aged stock there could be considerable variation in deformation strengths from those in this report. The results presented, however, are probably qualitatively correct insofar as the trends from the various treatments are concerned.

#### Creep Characteristics

The creep rates measured from the total-deformation tests are summarized in tables XVI and XVII. In most low-stress tests the creep rates were continuing to decrease with increased time of testing. These tables also show the minimum creep rates and time of transition to third-stage creep for the rupture tests.

The curves of logarithmic stress against logarithmic creep rate for heat 30276 are shown in figure 19. The hot-cold-worked condition had the highest creep resistance, the solution-treated and aged was intermediate, and the hot-rolled was weakest. The stress - creep-rate data were particularly erratic for the hot-cold-worked samples.

In figures 20(a) and 20(b), the stress-creep data at 1200°, 1350°, and 1500° F are assembled for the four conditions of treatment of heat Al726. These curves also show the pronounced influence of testing time on the observed creep rates. The pronounced influence of time on the observed creep rates leads to complex relations of creep strength, temperature, and treatment. It is also probably a contributing factor to the apparent erratic nature of the stress - creep-rate data. The stress - creep-rate characteristics of the hot-cold-worked material tested were more erratic than the other treatments particularly at 1500° F. Either the bars were not uniformly hot-cold-worked or, more probably, the instability of hot-cold-worked material at higher temperatures resulted in variability.

In general the number of tests run on heat Al726 was not sufficient to establish creep strength for 0.00001 percent per hour. The strengths for 0.0001 percent per hour were, however, quite well-established, except in those cases where creep rates were changing rapidly with the testing time. The creep strengths indicated by the available data are summarized in table XVIII. The influence of temperature and treatment on the creep strengths, shown graphically in figure 16, was:

1. Relative creep strengths were not well-defined at 1200° F, principally because the tests were incomplete for solution-treated and for solution-treated and aged material. The indications were, however, that 15-percent hot-cold-work at 1200° F nearly doubled the creep strengths. There was a wide difference in the creep resistance of the two heats in the as-rolled condition.

2. At 1350° F the superiority of the hot-cold-worked condition was greatly reduced for a rate of 0.0001 percent per hour and had disappeared for a rate of 0.00001 percent per hour. There was little difference between solution-treated (2100° F), solution-treated (2200° F) plus aged, and the hot-rolled stock for a rate of 0.0001 percent per hour. The hot-rolled was inferior at 0.00001 percent per hour.

3. At 1500° F the data indicate that hot-cold-work was of no benefit for a rate of 0.0001 percent per hour and was detrimental at slower creep rates. Aging appeared to be detrimental to creep strength at this temperature. As-rolled material was decidedly inferior.

The creep strengths for a rate of 0.0001 percent per hour are compared in table XIX with the extrapolated rupture strengths for fracture in 10,000 hours. This creep strength is often extrapolated as the stress to cause 1-percent total deformation in 10,000 hours. The rupture data in table XIX show that the creep strengths approached the rupture strengths for the hot-cold-worked materials at all three temperatures. The difference was rather small at 1350° F for the

solution-treated and for the solution-treated plus aged conditions. The creep and rupture strengths were equal for all four conditions tested at 1500° F. When the extrapolated rupture strengths approach the creep strength, there is considerable doubt regarding the reliability of extrapolation of the creep strength. Probably third-stage creep will occur prior to 10,000 hours with a consequent greater elongation in 10,000 hours than 1 percent, or the materials will fracture after about 1-percent creep.

### Stability Characteristics

Tensile, impact, and hardness tests and metallographic examination at room temperature were used to investigate structural stability during testing. The physical tests were confined to heat Al726 because unfractured specimens were available from all three temperatures of testing for total deformation.

The results of the tensile, impact, and hardness tests are in table XX. In all conditions of treatment there was a marked and progressive drop in ductility and impact strength after creep testing at 1200° and 1350° F. After testing at 1500° F these properties were either slightly less or slightly higher than after testing at 1350° F. It is particularly interesting to note that the solution-treated and hot-cold-worked stock underwent no greater change in this respect than the solution-treated and aged. The as-rolled material had slightly better ductility after testing than the other conditions.

The strength and hardness of all conditions, except the hot-cold-worked, were increased by creep testing at 1200° and still further increased by testing at 1350° F. Testing at 1500° F did not produce as much increase in strength and hardness. The hot-cold-worked stock progressively decreased in strength and hardness with increasing testing temperatures.

These fairly pronounced changes in strength and ductility as a result of testing indicate that the alloy undergoes considerable structural alteration during exposure to temperature and stress. These apparently are much greater at 1350° and 1500° F than at 1200° F for time periods up to 2000 hours. Aging for 24 hours at 1400° F after solution-treating at 2200° F apparently did very little to stabilize the structure. The hot-cold-worked material apparently underwent considerable relief of strain hardening during testing.

A metallographic examination was made of all of the original materials, of the longest duration rupture specimens, and of representative unfractured specimens from the design-data tests. The structural

changes were of a different type in heat 30276 from those in heat Al726 as is shown by the representative photomicrographs of figures 21 to 28. Both materials appeared to undergo both general and intergranular precipitation during testing at 1200° F. At 1350° and 1500° F, however, heat 30276 showed the presence of an agglomerated constituent which microscopically had all the characteristics of sigma phase. The precipitation in heat Al726 remained fine and well-dispersed after testing at these temperatures, the size of the particles merely increasing with testing temperatures.

The two rupture specimens from heat 30276 showing the strongest indication of sigma phase in the metallographic examination were checked by X-ray diffraction for sigma phase with the results shown in table XXI. A considerable number of lines corresponding closely in spacing to published diffraction values for sigma phase were found for the specimen tested at 1500° F and four lines for the specimen tested at 1350° F. These results confirm the presence of a sigma-type phase indicated by the metallographic examination. Because a number of the elements present in low-carbon N-155 alloy have been shown to form the sigma-phase structure (reference 4) and because the composition of the phase was not determined, the term "sigma-type phase" is used in this report. In addition to the sigma-phase lines, the columbium carbide in the low-carbon N-155 samples also gave diffraction lines.

The amount of sigma-type phase which formed in the samples from heat 30276 decreased with increasing solution temperatures and the structures after a 2200° F solution treatment were similar to those from heat Al726. Hot-cold-work apparently increased the tendency for the sigma-type phase to form in heat 30276. There were differences in grain size between the two heats although this factor seemed small in comparison with the differences in precipitation characteristics.

#### DISCUSSION OF RESULTS

This investigation was originally undertaken for the express purpose of providing representative design data for several commercial treatments. The results show that there can be quite wide differences in properties between two lots of the alloy which appear to be the same when compared on the basis of chemical composition or the usual room temperature physical properties.

The results do show that the usual generalizations regarding the effect of prior treatment on properties at high temperatures are correct. There can, however, be wide differences in the actual magnitude of the rupture, total deformation, or creep strengths as well as in ultimate elongation to fracture for different lots of the alloy.

Furthermore there can be wide variations in the temperature at which one type of treatment provides superior strength to another type. In this investigation, for instance, hot-cold-work provided superior rupture strength in one heat even for prolonged time periods at temperatures above  $1500^{\circ}\text{F}$ , while the other heat was inferior to solution-treated and aged material at temperatures below  $1500^{\circ}\text{F}$  at fairly short time periods. The as-rolled materials were particularly divergent in this respect. Thus there is not a single limiting temperature, even for a specific measure of strength, of superiority of one type of treatment over another for various lots of test stock.

The lower strength of heat 30276 than of heat A1726 at the higher temperatures and longer time periods was associated with the formation of a sigma-type phase during testing. The conditions under which it formed, the influence of prior treatment, and the effect on properties at high temperatures were similar to those observed in 18-8-Cb and 25-20 steel. (See reference 6.) The phase forms most extensively at about  $1350^{\circ}\text{F}$ , forms only slightly at  $1200^{\circ}\text{F}$ , and forms larger grains at  $1500^{\circ}\text{F}$ . High stresses and deformation, as in rupture testing, promote its formation. Increasingly higher solution temperatures reduce the amount of the phase which forms and finally eliminate it, at least as separate grains. Cold-work accelerates its formation. The formation of the sigma-type phase as separate grains is associated with steep stress - rupture-time curves, lowered creep resistance, and increased elongation in the rupture test.

Apparently solution-treating at  $2200^{\circ}\text{F}$  was nearly high enough to prevent grains of sigma-type phase from forming in heat 30276. This then could account for the similarity in rupture properties to those of heat A1726 after this treatment. Some sigma-type phase formed, however, causing some loss in creep strength which was offset by the increased elongation so that the rupture strengths were about equal after the  $2200^{\circ}\text{F}$  treatment.

The absence of identifiable grains of the sigma-type phase after testing at  $1200^{\circ}\text{F}$  indicates that either it does not form at that temperature or the rate of formation is extremely slow. The strength of heat 30276 was therefore comparable with that of heat A1726 at  $1200^{\circ}\text{F}$ . The reason why formation of sigma-type phase at higher temperatures apparently reduces strength in the rupture and creep tests is not evident from available information. The accumulation of precipitants into the grains of sigma phase leaving clean grain boundaries could account for the increased elongation.

The reason for the formation of sigma-type phase in specimens from heat 30276 and not in those from heat A1726 is not apparent. There is nothing in the chemical composition to account for the difference. The

only difference in the reported history of fabrication of the two was a finishing temperature of 1725° F for heat 30276 and 1910° F for heat A1726. It is therefore suggested that differences in hot-working conditions were responsible for the differences in properties of the two heats. It appeared as if a 2200° F solution treatment minimized such differences. It is believed, however, that the 2200° F treatments should not be relied upon for this purpose pending further verification over a wider range of hot-working conditions.

### CONCLUSIONS

Rupture data are reported at 1200°, 1350°, and 1500° F for two heats of low-carbon N-155 alloy bar stock in several typical conditions of treatment. The rupture test data were extended to 1650° and 1800° F for one of the heats. Design data in the form of the relationship between stress and time for various amounts of total deformation up to 1 percent were partially obtained for various typical treatments at 1200°, 1350°, and 1500° F. The results showed that:

1. The two heats differed in strength except when they were both solution-treated at 2200° F and aged at 1400° F prior to testing. The differences were small at 1200° F but pronounced at higher temperatures.
2. One heat had much steeper stress - rupture-time curves than the other. This was associated with the formation of grains of a sigma-type phase in the microstructure during testing at 1350° and 1500° F. The only difference observed between the two heats to which this difference in behavior could be attributed was a lower finishing temperature during the hot-rolling of the bar stock.
3. The results in general confirmed previous experience in that hot-cold-worked material loses its superiority in strength above some limiting temperature. This temperature decreases with the time period considered. The superiority also becomes less as the total deformation on which comparisons are based decreases. The hot-cold-worked condition, however, was found to maintain superiority to much higher temperature than had been thought to be the case. As-hot-rolled materials can have very variable properties, apparently associated with variations in hot-working conditions, little difference in solution-treated or solution-treated and aged material was observed.
4. While the general relations between prior treatment and properties at various temperatures are known the actual magnitude of the properties between different lots of an alloy can vary widely.

Consequently it is not possible to establish "typical" properties for various treatments except after high-temperature solution treatments which minimize differences in prior hot-working conditions.

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Ann Arbor, Mich., May 31, 1950

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TABLE I.- HEAT TREATMENTS AND TESTING CONDITIONS USED TO  
OBTAIN RUPTURE AND DESIGN DATA

Treatment	Tests conducted and temperatures <sup>1</sup> of testing			
	Rupture tests		Design-data tests	
	Heat 30276	Heat A1726	Heat 30276	Heat A1726
As-rolled	1200° to 1500° F	1200° to 1800° F	1200° F	1200° to 1500° F
As-rolled; aged at 1350° F for 24 hr	1200° to 1500° F	-----	-----	-----
As-rolled; 15% hot-cold-work at 1200° F	1200° to 1500° F	1200° to 1500° F	-----	-----
2100° F, 1 hr, W.Q. <sup>2</sup>	1200° to 1500° F	1200° to 1800° F	-----	1200° to 1500° F
2200° F, 1 hr, W.Q.	1200° to 1500° F	-----	-----	-----
2200° F, 1 hr, W.Q.; aged at 1400° F for 24 hr	1200° to 1500° F	1200° to 1800° F	-----	1200° to 1500° F
2200° F, 1 hr, W.Q.; aged at 1350° F for 50 hr	1200° F	-----	1200° F	-----
2050° F, 2 hr, W.Q.; 15% hot-cold-work at 1200° F	1200° to 1500° F	1200° to 1800° F	-----	1200° to 1500° F
2050° F, 2 hr, W.Q.; 25% hot-cold-work at 1200° F	1200° to 1500° F	-----	1200° F	-----

<sup>1</sup>Test temperatures were 1200°, 1350°, 1500°, 1650°, and 1800° F; table shows range of temperatures at which tests were made.

<sup>2</sup>W.Q. - Water-quenched.



TABLE II.- ROOM-TEMPERATURE PHYSICAL PROPERTIES OF LOW-CARBON

N-155 ALLOY BAR STOCK FROM TWO HEATS

Heat	Treatment (1)	Brinell hardness	Tensile strength (psi)	Offset yield strength (psi)			Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)
				0.02 percent	0.1 percent	0.2 percent			
30276	As-rolled	233	128,500	72,500	76,500	78,500	57,500	40.5	55.7
A1726	As-rolled	228	127,200	63,000	73,200	77,400	46,500	40	51.0
30276	AR+Ag	214	124,500	52,700	62,500	66,300	37,500	36	38.2
30276	AR+HCW	328	156,700	121,500	135,500	140,000	82,500	22	43.3
A1726	AR+HCW	337							
30276	ST(2100)	197	117,250	38,500	52,000	57,000	17,500	47	63.2
A1726	ST(2100)	207	117,000	45,700	52,800	56,300	36,000	50	67.6
30276	ST(2200)	205	115,750	42,000	53,000	57,000	25,000	46.5	64.3
30276	ST+Ag(1400)	221	119,250	48,000	61,000	65,000	25,000	32	39.8
A1726	ST+Ag(1400)	228	118,900	47,800	55,800	59,400	37,000	38	46.8
30276	ST+Ag(1350)	213	118,000	50,000	57,500	60,000	32,500	36	41.9
30276	ST+15%HCW	296	145,500	110,500	120,500	124,500	65,000	26	53.2
A1726	ST+15%HCW	321	144,000	107,500	117,200	120,300	97,500	24	57.0
30276	ST+25%HCW	318	156,000	104,000	130,000	137,500	70,000	22	48.1

<sup>1</sup>Treatments:

- AR+Ag - As-rolled; 1350° F, 24 hr
- AR+HCW - As-rolled; 15% hot-cold-work at 1200° F
- ST(2100) - 2100° F, 1 hr, water-quenched
- ST(2200) - 2200° F, 1 hr, water-quenched
- ST+Ag(1400) - 2200° F, 1 hr, water-quenched; 1400° F, 24 hr
- ST+Ag(1350) - 2200° F, 1 hr, water-quenched; 1350° F, 50 hr
- ST+15%HCW - 2050° F, 2 hr, water-quenched; 15% hot-cold-work at 1200° F
- ST+25%HCW - 2050° F, 2 hr, water-quenched; 25% hot-cold-work at 1200° F



TABLE III.- RUPTURE TEST DATA AT 1200° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK

Treatment	Heat	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
As-rolled	30276	<sup>a</sup> 55,000	8.5	<sup>b</sup> 9.5	8.5
		<sup>a</sup> 50,000	75	17	23.3
		<sup>a</sup> 45,000	252	19	23.3
		<sup>a</sup> 40,000	610	34	48.3
As-rolled	A1726	50,000	53	<sup>c</sup> 2	10.2
		49,000	80	<sup>c</sup> 5	6.1
		45,000	472	12	11.3
As-rolled + aged 24 hr at 1350° F	30276	<sup>a</sup> 50,000	123	12	49.2
		<sup>a</sup> 45,000	241	38	55.3
		<sup>a</sup> 41,000	411	33	55.3
As-rolled + 15% hot-cold- work at 1200° F	30276	<sup>a</sup> 60,000	157	6	20.6
		<sup>a</sup> 55,000	325	8	24.1
		<sup>a</sup> 50,000	845	6.5	17.9
As-rolled + 15% hot-cold- work at 1200° F	A1726	60,000	63	1	3.5
		57,500	94	1	2.2
		55,000	712	1	2.8
1 hr, 2100° F, W.Q. <sup>d</sup>	30276	<sup>a</sup> 50,000	35	<sup>b</sup> 9	17.8
		<sup>a</sup> 45,000	141	<sup>b</sup> 6	10.9
		<sup>a</sup> 40,000	1003	16	17.8
1 hr, 2100° F, W.Q.	A1726	45,000	17	<sup>b</sup> 8	18.6
		43,000	136	4	7.7
		40,000	725	<sup>b</sup> 4	11.8
		37,000	1845	13	16.4
1 hr, 2200° F, W.Q.	30276	<sup>a</sup> 50,000	4	<sup>b</sup> 5	26.7
		<sup>a</sup> 45,000	29	4	15.6
		<sup>a</sup> 40,000	247	<sup>b</sup> 6	6.2
		<sup>a</sup> 37,500	1500	-----	-----
1 hr, 2200° F + 24 hr at 1400° F	30276	<sup>a</sup> 54,000	49	<sup>b</sup> 12	18.3
		<sup>a</sup> 50,000	118	14	17.8
		<sup>a</sup> 47,000	133	18	23.3
		<sup>a</sup> 45,000	398	21	30.8
1 hr, 2200° F, W.Q.; 24 hr at 1400° F	A1726	50,000	66	10	11.7
		47,000	101	9	8.8
		46,000	144	10	9.8
		44,000	446	10	14.5
1 hr, 2200° F, W.Q.; 50 hr at 1350° F	30276	<sup>a</sup> 50,000	53	<sup>b</sup> 12	13.3
		<sup>a</sup> 45,000	145	<sup>b</sup> 10	16.7
		<sup>a</sup> 40,000	479	<sup>b</sup> 14	21.2
		35,000	3301	19	21.6
2 hr, 2050° F, W.Q.; 15% hot- cold-work at 1200° F	30276	<sup>a</sup> 60,000	167	1	1.5
		<sup>a</sup> 55,000	389	8	21.0
		<sup>a</sup> 52,000	1556	4	16.4
2 hr, 2050° F, W.Q.; 15% hot- cold-work at 1200° F	A1726	60,000	14.5	2	7.5
		55,000	147	5	3.5
		52,000	270	2	3.0
		49,000	210	<sup>b</sup> 3	3.5
		49,000	137	<sup>c</sup> 3	5.6
		48,000	942	1.5	1.8
2 hr, 2050° F, W.Q.; 25% hot- cold-work at 1200° F	30276	<sup>a</sup> 70,000	19	2	5.7
		<sup>a</sup> 65,000	200	4	11.0
		<sup>a</sup> 60,000	493	5	18.9
		<sup>a</sup> 55,000	1142	5	21.6

<sup>a</sup>0.160-in.-diam. test specimen. All other specimens were 0.250-in.-diam.<sup>b</sup>Fractured in gage mark.<sup>c</sup>Fractured in fillet.<sup>d</sup>W.Q. - Water-quenched.

TABLE IV.- RUPTURE TEST DATA AT 1350° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK

Treatment	Heat	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
As-rolled	30276	30,000	130	42	45.3
		25,000	264	41	48.1
		20,000	769	31	35.6
As-rolled	A1726	35,000	86	18	21.6
		32,500	156	36	35.5
		30,000	623	23	19.9
As-rolled + aged 24 hr at 1350° F	30276	30,000	51	50	62.5
		22,000	351	38	50.2
		20,000	639	30	36.8
As-rolled + 15% hot- cold-work at 1200° F	30276	35,000	95	19	27.1
		30,000	172	19	22.6
		22,000	499	12	14.6
As-rolled + 15% hot- cold-work at 1200° F	A1726	40,000	66	6	6.9
		35,000	208	8	9.9
		30,000	456	5	4.1
		25,000	1693	5	3.2
1 hr, 2100° F, W.Q. <sup>a</sup>	30276	30,000	117	35	38.4
		25,000	432	21	25.9
		22,000	997	23	32.5
1 hr, 2100° F, W.Q.	A1726	30,000	75	10	11.8
		29,000	222	31	26.1
		27,000	400	35	33.5
		25,000	696	24	26.1
1 hr, 2200° F, W.Q.	30276	32,000	65	b13	18.8
		30,000	165	36	36.0
		27,000	328	35	31.4
		25,000	439	b16	21.0
1 hr, 2200° F + 24 hr at 1400° F	30276	33,000	32	35	35.9
		30,000	136	47	46.9
		25,000	726	32	37.3
1 hr, 2200° F, W.Q. + 24 hr at 1400° F	A1726	35,000	48	25	24.9
		33,000	62	16	13.9
		30,000	226	30	34.6
		26,000	441	44	41.6
2 hr, 2050° F, W.Q. + 15% hot-cold-work at 1200° F	30276	39,000	79	b13	27.2
		35,000	250	9	17.4
		30,000	593	5	7.3
2 hr, 2050° F, W.Q. + 15% hot-cold-work at 1200° F	A1726	38,000	183	7	13.1
		36,000	300	12	17.6
		33,000	564	9	14.4
2 hr, 2050° F, W.Q.; 25% hot-cold-work at 1200° F	30276	39,000	132	7	11.5
		33,000	319	4	5.5
		30,000	446	6	8.2

<sup>a</sup>W.Q. - Water-quenched.<sup>b</sup>Fractured in gage mark.

TABLE V.- RUPTURE TEST DATA AT 1500° F FOR LOW-CARBON

## N-155 ALLOY BAR STOCK

Treatment	Heat	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
As-rolled	30276	20,000	16.5	26	60.6
		15,000	64	48	44.0
		12,000	194	33	35.1
		9,000	430	28	28.6
As-rolled	A1726	15,000	130	25	25.2
		13,500	458	23	24.0
		13,000	433	22	19.8
		12,000	747	17	20.0
As-rolled + aged 24 hr at 1350° F	30276	17,500	27	46	53.2
		13,000	102	40	42.3
		9,000	424	27	28.9
As-rolled + 15% hot- cold-work at 1200° F	30276	22,000	14	35	37.3
		16,000	53	31	30.6
		9,500	272	22	24.6
		7,500	493	44	29.1
As-rolled + 15% hot- cold-work at 1200° F	A1726	20,000	81	12	10.5
		17,000	240	12	11.8
		15,000	256	8	6.9
		12,000	890	10	5.6
1 hr, 2100° F, W.Q. <sup>a</sup>	30276	17,500	97	40	54.5
		15,000	334	43	51.9
		13,000	577	34	42.7
1 hr, 2100° F, W.Q.	A1726	18,000	109	58	54.8
		16,500	241	47	51.4
		15,000	672	45	47.4
1 hr, 2200° F, W.Q.	30276	20,000	71	60	52.7
		17,500	255	40	49.3
		15,000	615	36	40.8
1 hr, 2200° F + 24 hr at 1400° F	30276	19,500	160	48	54.7
		17,500	239	32	50.5
		14,000	1131	23	31.3
1 hr, 2200° F, W.Q. + 24 hr at 1400° F	A1726	20,000	131	33	39.4
		18,000	260	23	31.9
		16,000	760	52	47.0
		14,600	1033	33	44.1
2 hr, 2050° F, W.Q. + 15% hot-cold-work at 1200° F	30276	20,000	136	16	17.7
		17,500	303	5.5	3.4
		15,000	486	9	5.4
		13,000	421	12	9.9
2 hr, 2050° F, W.Q. + 15% hot-cold-work at 1200° F	A1726	24,000	104	14	24.0
		20,000	321	10	14.5
		18,000	739	6	6.9
2 hr, 2050° F, W.Q. + 25% hot-cold-work at 1200° F	30276	20,000	100	10	11.4
		18,000	129	c6	7.8
		13,000	340	10	10.6

aW.Q. - Water-quenched.

bFractured in fillet.

cFractured in gage mark.



TABLE VI.- RUPTURE TEST DATA AT 1650° F FOR LOW-CARBON

## N-155 ALLOY BAR STOCK

Treatment	Heat	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
As-rolled	A1726	7,000	148	19	20.5
		5,500	334	19	16.9
		5,000	1051	8	11.3
1 hr, 2200° F, W.Q. <sup>1</sup>	A1726	9,000	192	39	39.2
		8,400	359	22	23.1
		8,000	647	25	27.9
1 hr, 2200° F + 24 hr at 1400° F	A1726	13,000	46	39	43.4
		9,000	385	22	23.3
		7,400	1384	17	19.9
2 hr, 2050° F, W.Q. + 15% hot-cold-work at 1200° F	A1726	14,000	65	8	15.4
		11,000	165	11	8.6
		9,000	301	8	9.1
		7,000	676	7	9.2
		6,200	1419	(2)	7.0
		6,000	676	24	18.3
		5,500	977	11	15.4

<sup>1</sup>W.Q. - Water-quenched.<sup>2</sup>Piece of specimen near fracture lost.

TABLE VII.- RUPTURE TEST DATA AT 1800° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK

Treatment	Heat	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
As-rolled	A1726	3000	115	36	24.0
		2300	228	(1)	14.0
		1800	563	40	12.5
		1500	847	10	21.2
1 hr, 2100° F, W.Q. <sup>2</sup>	A1726	6600	37.5	31	28.0
		5500	108	12	13.2
		5000	223	20	22.1
		4500	243	13	10.0
		4500	272	14	14.5
		3900	317	21	19.6
		3500	424	18	17.5
		2800	2128	12	14.5
1 hr, 2200° F + 24 hr at 1400° F	A1726	7000	43.5	32	26.1
		5000	188	9	9.3
		3800	485	10	7.5
		3300	959	8	9.0
2 hr, 2050° F, W.Q. + 15% hot-cold-work at 1200° F	A1726	6000	22.5	24	28.9
		4500	51	24	26.0
		3300	175	24	16.0
		3000	271	21	14.7
		2100	474	30	19.0
		1850	1004	29	16.0

<sup>1</sup>Piece of specimen near fracture lost.<sup>2</sup>W.Q. - Water-quenched.

TABLE VIII.- COMPARATIVE RUPTURE PROPERTIES AT 1200° TO 1800° F FROM TWO  
HEATS OF LOW-CARBON M-135 ALLOY BAR STOCK

Treatment	Temperature (°F)	Heat 30276					Heat A1726				
		Rupture strength (psi)			Estimated rupture elongation (percent in 1 in.)		Rupture strength (psi)			Estimated rupture elongation (percent in 1 in.)	
		100 hr	1000 hr	10,000 hr	100 hr	1000 hr	100 hr	1000 hr	10,000 hr	100 hr	1000 hr
As-rolled	1200	49,500	37,500	28,000	17	34	48,000	43,000	38,000	5	12
	1350	32,000	18,500	10,500	42	31	34,000	29,000	24,000	20	23
	1500	13,500	7,800	4,500	40	28	15,500	11,500	8,600	25	17
	1650						7,800	4,100	2,100	19	8
	1800						3,150	1,400	620	36	10
2100° F, 1 hr, W.Q. <sup>1</sup>	1200	46,500	40,000	34,000	7	16	44,000	38,500	34,000	4	10
	1350	31,000	22,000	16,000	35	23	30,500	24,500	20,000	15	24
	1500	17,500	12,500	9,000	40	34	18,000	14,500	11,500	58	45
	1650						9,600	7,700	6,300	40	25
	1800						5,500	3,350	2,000	12	12
2200° F, 1 hr, W.Q.; 1400° F, 24 hr	1200	50,000	42,000	35,000	14	21	47,000	42,000	38,000	10	10
	1350	30,500	24,000	19,000	47	32	32,000	25,500	20,000	25	44
	1500	21,000	14,000	9,200	50	23	21,000	14,500	10,000	35	33
	1650						11,500	7,700	5,400	30	20
	1800						5,700	3,300	1,900	25	8
As-rolled; 15% hot-cold-work at 1200° F	1200	63,000	48,000	36,000	6	6	59,000	54,000	50,000	1	1
	1350	35,000	18,000	9,300	19	12	37,500	27,000	19,000	6	5
	1500	12,800	5,800	2,700	28	44	18,700	11,800	7,300	12	10
2050° F, 2 hr, W.Q.; 15% hot-cold-work at 1200° F	1200	62,000	53,500	46,000	1	5	55,000	48,000	42,000	3	1.5
	1350	38,000	28,500	21,000	12	5	41,000	31,500	23,000	6	9
	1500	22,000	12,500	7,000	16	12	24,000	17,000	12,000	14	6
	1650						12,300	6,500	3,400	10	10
	1800						3,800	1,850	900	24	30
As-rolled; 1350° F, 24 hr	1200	51,000	35,500	24,000	12	33					
	1350	27,000	18,500	13,000	45	30					
	1500	13,000	7,400	4,300	41	27					
2200° F, 1 hr, W.Q.	1200	42,000	38,000	34,000	4	6					
	1350	30,500	23,500	18,000	35	16					
	1500	19,000	14,500	11,000	50	36					
2050° F, 2 hr, W.Q.; 25% hot-cold-work at 1200° F	1200	66,000	56,000	45,000	3	5					
	1350	41,500	25,000	15,000	7	6					
	1500	20,000	9,000	3,900	10	10					
2200° F, 1 hr, W.Q.; 1350° F, 50 hr	1200	46,500	38,500	32,000	11	15					

<sup>1</sup>W.Q. - Water-quenched.



TABLE IX.- TEMPERATURES AT WHICH RUPTURE STRENGTHS OF OTHER TREATMENTS FELL  
BELOW THOSE RESULTING FROM WATER-QUENCHING FROM 2200° F  
AND AGING AT 1400° F FOR 24 HOURS

Other treatments	Temperature (°F)					
	100 hr for rupture		1000 hr for rupture		10,000 hr for rupture	
	Heat A1726	Heat 30276	Heat A1726	Heat 30276	Heat A1726	Heat 30276
2050° F, 2 hr, W.Q. + 15% hot-cold-work	1680	(>1500)	1600	1450	1560	1425
2050° F, 2 hr, W.Q. + 25% hot-cold-work	----	1485	----	1365	----	1225
As-rolled + 15% hot-cold-work	1455	1400	1400	1250	1360	1200
As-rolled	1390	1375	1420	(1)	1460	(1)
As-rolled + 24 hr at 1350° F	----	(1)	----	(1)	----	(1)
2100° F, 1 hr, W.Q. <sup>2</sup>	(1)	(1)	(3)	(1)	(4)	1200
2200° F, 1 hr, W.Q.	----	(1)	----	(5)	----	(6)

<sup>1</sup>Strengths were less than those of the solution-treated and aged at all temperatures of testing.

<sup>2</sup>W.Q. - Water-quenched.

<sup>3</sup>Strengths were less than those of the solution-treated and aged up to 1500° F and the two were equal at higher temperatures.

<sup>4</sup>Higher rupture strengths than those of the solution-treated and aged except at 1200° and 1800° F.

<sup>5</sup>Strengths were less than those of the solution-treated and aged up to 1375° F and the two were equal at higher temperatures.

<sup>6</sup>Lower rupture strengths than those of solution-treated and aged except at 1425° F and above.



TABLE X.- DATA ON STRESS AND TIME FOR TOTAL DEFORMATION AT 1200° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK FROM HEAT 30276

Treatment	Stress (psi)	Initial deformation (percent)	Time (hr) for total deformation of -				Transition to third-stage creep		Rupture data	
			0.1 percent	0.2 percent	0.5 percent	1.0 percent	Time (hr)	Deformation (percent)	Rupture time (hr)	Elonga- tion (percent)
As-rolled	10,500	0.044	990							
	11,000	.044	361							
	12,500	.048	470	<sup>a</sup> 2450						
	13,500	.061	230	<sup>a</sup> 1600						
	15,000	.066	145	1310						
	18,000	.076	37	432	2948					
	20,000	.100	-----	90	950					
	22,500	.128	-----	41	345	<sup>a</sup> 1250				
	25,000	.128	-----	28	236	755				
	30,000	.148	-----	9	110	273				
	40,000	.331	-----	-----	3	14	360	8.0	610	34
	45,000	1.26	-----	-----	-----	-----	150	8.6	252	19
2200° F, 1 hr, W.Q. <sup>b</sup> + 50 hr at 1350° F	15,000	0.066	640							
	17,500	.074	175	<sup>a</sup> 2800						
	20,000	.096	1.5	475						
	25,000	.123	-----	73	<sup>a</sup> 1045					
	30,000	.145	-----	23	190	620				
	35,000	.221	-----	-----	26	110	2700	10.0	3301	19
	40,000	.386	-----	-----	2.5	13	290	4.95	497	14
2050° F, 1 hr, W.Q. + 25% hot- cold-work at 1200° F	15,940	0.062	<sup>a</sup> 2500							
	20,000	.092	10	<sup>a</sup> 2400						
	30,000	.138	-----	77	<sup>a</sup> 4300					
	40,000	.169	-----	8	470					
	55,000	.232	-----	-----	5	925	900	0.94	1142	5
	60,000	.253	-----	-----	3.5	305	425	1.30	493	5
	65,000	.274	-----	-----	1	8	125	1.60	200	4

<sup>a</sup>Estimated by creep data extrapolation.<sup>b</sup>W.Q. - Water-quenched.

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TABLE XI.- DATA ON STRESS AND TIME FOR TOTAL DEFORMATION AT 1200° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK FROM HEAT A1726

Treatment	Stress (psi)	Initial deformation (percent)	Time (hr) for total deformation of -				Transition to third-stage creep		Rupture data	
			0.1 percent	0.2 percent	0.5 percent	1.0 percent	Time (hr)	Deformation (percent)	Rupture time (hr)	Elongation (percent)
As-rolled	15,000	0.0550	695	—	—	—	—	—	—	—
	20,000	.0905	7	598	—	—	—	—	—	—
	25,000	.1162	—	222	—	—	—	—	—	—
	30,000	.1273	—	42	557	<sup>a</sup> 2600	—	—	—	—
	32,500	.1432	—	15	140	525	—	—	—	—
	45,000	.265	—	—	4	18	190	3.8	472	12
	49,000	.313	—	—	—	6	—	—	80	5
2100° F, 1 hr, W.Q. <sup>b</sup>	30,000	.160	—	14	370	1115	—	—	—	—
	32,500	.225	—	—	265	770	—	—	—	—
	35,000	.320	—	—	68	330	—	—	—	—
	37,000	.430	—	—	2	22	920	3.65	1845	13
	40,000	.870	—	—	—	4	—	—	725	4
	25,000	0.1125	—	115	1223	—	—	—	—	—
	30,000	.1366	—	32	198	632	1150	1.6	—	—
2200° F, 1 hr, W.Q. + 24 hr at 1400° F	34,000	.1759	—	2.2	49	130	—	—	—	—
	37,000	.202	—	—	10	30	—	—	—	—
	44,000	.636	—	—	—	7	265	4.5	446	10
	46,000	.732	—	—	—	2	94	5.4	144	10
	30,000	0.136	—	190	<sup>c</sup> 1315	—	—	—	—	—
2050° F, 2 hr W.Q. + 15% hot- cold-work at 1200° F	37,000	.168	—	22	<sup>c</sup> 895	—	—	—	—	—
	40,000	.181	—	4	—	—	—	—	—	—
	40,000	.181	—	3	—	—	—	—	—	—
	42,000	.190	—	.5	<sup>c</sup> 12	—	—	—	—	—
	48,000	.217	—	—	13	200	—	—	942	1.5
	49,000	.220	—	—	16	—	—	—	137	43
	49,000	.220	—	—	18	—	—	—	210	43
	52,000	.235	—	—	10	95	220	1.02	270	2.0
	55,000	.249	—	—	6	97	—	—	147	5.0
	30,000	0.136	—	190	<sup>c</sup> 1315	—	—	—	—	—
	37,000	.168	—	22	<sup>c</sup> 895	—	—	—	—	—

<sup>a</sup>Estimated by creep data extrapolation.<sup>b</sup>W.Q. - Water-quenched.<sup>c</sup>0.25-percent deformation.<sup>d</sup>Fractured in gage mark or fillet.

TABLE XII.- DATA ON STRESS AND TIME FOR TOTAL DEFORMATION AT 1350° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK FROM HEAT A1726

Treatment	Stress (psi)	Initial deformation (percent)	Time (hr) for total deformation of -				Transition to third-stage creep		Rupture data	
			0.1 percent	0.2 percent	0.5 percent	1.0 percent	Time (hr)	Deformation (percent)	Rupture time (hr)	Elonga- tion (percent)
As-rolled	10,000	0.0467	173	1555						
	15,000	.0769	6	225						
	20,000	.0957	.5	25	346	1510				
	22,500	.1087	-----	5.4	48	8210				
	30,000	.1810	-----	-----	9	41	335	3.5	623	23
	32,500	.240	-----	-----	2	6	89	8.4	156	36
	35,000	.306	-----	-----	2	6			86	18
2100° F, 1 hr, W.Q. <sup>b</sup>	12,500	0.053	19	192						
	15,000	.063	8	47	464					
	17,500	.074	1.2	8	67	725				
	20,000	.085	.5	12	66	273				
	25,000	.095	-----	1.6	6.5	20	405	7.4	696	24
	27,000	.112	-----	-----	5	13	220	9.0	400	35
	29,000	.135	-----	-----	2	6	95	6.4	222	31
2200° F, 1 hr, W.Q. + 24 hr at 1400° F	10,000	0.0483	162	1240						
	15,000	.0731	17	186						
	17,500	.0781	2.2	60	650					
	20,000	.1024	-----	-----	68	273				
	26,000	.150	-----	-----	5	14	270	7.2	441	44
	30,000	.183	-----	-----	-----	5	90	6.2	226	30
2050° F, 2 hr, W.Q. + 15% hot- cold-work at 1200° F	15,000	0.0680	75	1362						
	20,000	.0910	-----	73						
	22,500	.1080	-----	71						
	25,000	.1160	-----	35	700	81850	1410	0.87		
	33,000	.149	-----	-----	24	80	312	1.6	564	9
	36,000	.162	-----	-----	17	52	195	1.6	300	12
	38,000	.175	-----	-----	6	24	92	1.6	184	7

<sup>a</sup> Estimated by creep data extrapolation.<sup>b</sup> W.Q. - Water-quenched.

TABLE XIII.- DATA ON STRESS AND TIME FOR TOTAL DEFORMATION AT 1500° F FOR LOW-CARBON

N-155 ALLOY BAR STOCK FROM HEAT A1726

Treatment	Stress (psi)	Initial deformation (percent)	Time (hr) for total deformation of -				Transition to third-stage creep		Rupture data	
			0.1 percent	0.2 percent	0.5 percent	1.0 percent	Time (hr)	Deformation (percent)	Rupture time (hr)	Elongation (percent)
As-rolled	7,500	0.0340	58	550						
	9,000	.0442	25	197	1520		1225	0.42		
	10,000	.0532	13							
	10,500	.0564	7	75						
	12,000	.0580	-----	---	-----	18	400	3.4	747	20
	13,000	.0630	-----	---	-----	8	110	2.6	432	22
	13,500	.0680	-----	---	-----	---	260	3.5	458	23
	15,000	.0790	-----	---	-----	---	72	6.6	130	25
2100° F, 1 hr, W.Q. <sup>a</sup>	8,500	0.0409	44	400						
	10,000	.0433	20	214						
	12,000	.0546	2.0	33	490	867	410	0.45		
	15,000	.181	-----	---	2	12	234	3.8	671	45
	16,500	.240	-----	---	-----	1	136	8.8	241	47
2200° F, 1 hr, W.Q. + 24 hr at 1400° F	7,000	0.0328	370							
	9,000	.0422	42	608	-----	---	1250	0.24		
	10,000	.0552	26	200	-----	---	800	.25		
	12,000	.0571	6	88	593	836	310	.30		
	14,600	.0695	-----	---	16	43	330	1.8	1033	33
	16,000	.0763	-----	7	47	150	140	.86	760	52
	18,000	.0857	-----	---	5	15	95	3.3	260	23
	29,000	.0954	-----	---	1	3	40	.32	131	33
2050° F, 2 hr, W.Q. + 15% hot- cold-work at 1200° F	10,000	0.0515	6	380						
	11,500	.0747	-----	53						
	14,000	.0959	-----	8	b <sub>56</sub>					
	18,000	.116	-----	---	5.5	10	590	3.0	739	6
	20,000	.136	-----	---	-----	3	143	3.0	321	10

<sup>a</sup>W.Q. - Water-quenched.<sup>b</sup>Estimated by creep data extrapolation.

TABLE XIV.- TIME - TOTAL-DEFORMATION STRENGTHS AT 1200° F

FOR LOW-CARBON N-155 ALLOY BAR

STOCK FROM HEAT 30276

Treatment (a)	Total deformation (percent)	Stress (psi) to cause total deformation in -			
		10 hr	100 hr	1000 hr	2000 hr
As-rolled	0.1	21,000	15,500	10,500	9,000
ST+Ag(1350)	.1	19,000	17,800	14,100	<sup>b</sup> 12,800
ST+25%HCW	.1	20,000	18,200	16,700	16,000
As-rolled	.2	29,500	19,800	15,000	13,600
ST+Ag(1350)	.2	33,500	23,500	19,000	18,000
ST+25%HCW	.2	37,000	29,800	22,600	20,600
As-rolled	.5	36,500	30,200	20,000	18,700
ST+Ag(1350)	.5	37,500	31,300	25,000	23,200
ST+25%HCW	.5	54,500	45,000	36,000	33,000
As-rolled	1.0	41,000	33,200	23,600	20,500
ST+Ag(1350)	1.0	41,000	34,900	28,700	<sup>b</sup> 26,900
ST+25%HCW	1.0	64,500	61,500	54,000	50,000
As-rolled	Transition	-----	47,500	34,000	<sup>b</sup> 30,000
ST+Ag(1350)	Transition	-----	42,300	37,000	35,500
ST+25%HCW	Transition	-----	66,000	54,000	50,000

<sup>a</sup>Treatments: ST+Ag(1350) - 2200° F, 1 hr, water-quenched;  
1350° F, 50 hr.  
ST+25%HCW - 2050° F, 2 hr, water-quenched; 25% hot-  
cold-work at 1200° F.

<sup>b</sup>Estimated.



TABLE XV.- TIME - TOTAL-DEFORMATION STRENGTHS AT 1200°, 1350°, AND 1500° F FOR  
LOW-CARBON N-155 ALLOY BAR STOCK FROM HEAT A1726

Treatment (a)	Total deformation (percent)	Stress (psi) to cause total deformation in -			
		10 hr	100 hr	1000 hr	2000 hr
1200° F					
As-rolled	0.1	19,500	17,200	14,600	b14,000
ST(2100)	.1				
ST+Ag(1400)	.1				
ST+15%ECW	.1				
As-rolled	.2	35,000	26,800	18,700	b16,500
ST(2100)	.2	30,500	27,000		
ST+Ag(1400)	.2	32,400	26,000	b19,500	
ST+15%ECW	.2	38,300	32,300	b25,000	b22,500
As-rolled	.5	42,000	34,800	27,300	b25,000
ST(2100)	.5	36,100	34,700	23,500	b18,500
ST+Ag(1400)	.5	38,000	32,000	25,500	23,600
ST+15%ECW	.5	52,000			
As-rolled	1.0	47,000	39,500	31,700	b29,500
ST(2100)	1.0	38,500	36,100	30,700	26,500
ST+Ag(1400)	1.0	40,500	34,700	28,800	b27,000
ST+15%ECW	1.0	-----	53,000		
As-rolled	Transition	-----	b47,000		
ST(2100)	Transition	-----		b37,000	
ST+Ag(1400)	Transition	-----	45,800	31,500	b29,000
ST+15%ECW	Transition	-----	b22,000		
1350° F					
As-rolled	0.1	14,200	10,800	b7,400	
ST(2100)	.1	14,000	b9,500		
ST+Ag(1400)	.1	15,400	11,000	b6,500	
ST+15%ECW	.1	-----	b14,300		
As-rolled	.2	22,000	16,600	11,000	9,400
ST(2100)	.2	20,500	14,300	b8,200	
ST+Ag(1400)	.2	21,500	16,000	10,500	8,900
ST+15%ECW	.2	27,500	21,700	15,800	14,000
As-rolled	.5	28,700	22,300	16,000	b14,000
ST(2100)	.5	24,300	18,800	13,300	b11,800
ST+Ag(1400)	.5	24,200	20,100	16,000	b14,800
ST+15%ECW	.5	37,500	30,600	24,000	22,000
As-rolled	1.0	32,500	26,000	19,600	b17,700
ST(2100)	1.0	27,000	21,300	16,900	15,500
ST+Ag(1400)	1.0	27,300	22,200	b17,200	
ST+15%ECW	1.0	41,000	34,000	27,000	b24,800
As-rolled	Transition	-----	32,200	b28,000	
ST(2100)	Transition	-----	28,700	22,500	b20,500
ST+Ag(1400)	Transition	-----	29,500	b21,300	
ST+15%ECW	Transition	-----	38,500	26,500	23,000
1500° F					
As-rolled	0.1	10,100	6,800	b3,500	
ST(2100)	.1	10,500	7,000		
ST+Ag(1400)	.1	11,300	8,500	5,800	b5,000
ST+15%ECW	.1	b9,200			
As-rolled	.2	-----	10,000	6,600	b5,500
ST(2100)	.2	13,200	10,800	6,500	b5,000
ST+Ag(1400)	.2	15,100	11,600	8,000	b7,000
ST+15%ECW	.2	13,700	11,200	9,000	b8,000
As-rolled	.5	-----	-----	b9,700	
ST(2100)	.5	14,200	b12,800	b10,200	
ST+Ag(1400)	.5	17,500	15,000	b11,000	b9,500
ST+15%ECW	.5	17,000	b13,200		
As-rolled	1.0	13,000			
ST(2100)	1.0	15,100	b13,700	b11,700	
ST+Ag(1400)	1.0	18,700	16,300	11,500	b10,000
ST+15%ECW	1.0	18,000	b14,200		
As-rolled	Transition	-----	14,500	9,500	b8,000
ST(2100)	Transition	-----	-----	b8,000	
ST+Ag(1400)	Transition	-----	17,200	9,600	7,500
ST+15%ECW	Transition	-----	20,500		

<sup>a</sup>Treatments:  
ST(2100) - 2100° F, 1 hr, water-quenched.  
ST+Ag(1400) - 2200° F, 1 hr, water-quenched; 1400° F, 24 hr.  
ST+15%ECW - 2050° F, 2 hr, water-quenched; 15% hot-cold-work at 1200° F.  
<sup>b</sup>Estimated.

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TABLE XVI.- CREEP DATA AT 1200° F FOR LOW-CARBON N-155 ALLOY

BAR STOCK FROM HEAT 30276

Treatment	Stress (psi)	Duration (hr)	Initial deformation (percent)	Creep rate (percent/hr) at -			
				500 hr	1000 hr	1500 hr	Minimum <sup>a</sup>
As-rolled	10,500	1290	0.044	0.000050	0.000021		
	11,000	1475	.044	.000045	.000029	0.000029	
	12,500	1030	.048	.000062	.000053		
	13,500	1270	.061	.000083	.000058		
	15,000	1406	.066	.000096	.000067	.000067	
	18,000	3430	.076	.000200	.000155	.000135	
	20,000	1004	.100	.000318	.000268		
	22,500	1006	.128	.000600	.000480		
	25,000	1000	.128	.00090	.000615		
	30,000	1400	.148	.00166	.00105	.00105	
	40,000	<sup>b</sup> 360	.331	-----	-----	-----	0.015
	45,000	<sup>b</sup> 150	1.26	-----	-----	-----	.038
2200° F, 1 hr, W.Q. <sup>c</sup> + 50 hr at 1350° F	15,000	1415	0.066	0.000027	0.000019	0.000019	
	17,500	1265	.074	.000034	.000026		
	20,000	1010	.096	.000120	.000100		
	25,000	1004	.123	.000275	.000220		
	30,000	1004	.145	.00110	.000880		
	35,000	<sup>b</sup> 2700	.221	.00320	.00350	.00350	0.0032
	40,000	<sup>b</sup> 290	.386	-----	-----	-----	.0100
	45,000	-----	-----	-----	-----	-----	.0205
2050° F, 1 hr, W.Q. + 25% hot-cold-work at 1200° F	15,940	1818	0.062	0.0000105	0.0000085	0.0000085	
	20,000	1372	.092	.0000380	.0000380		
	30,000	1868	.138	.000105	.000080	.000058	
	40,000	1218	.169	.000380	.000110		
	55,000	<sup>b</sup> 900	.232	-----	-----	-----	0.00038
	60,000	<sup>b</sup> 425	.253	-----	-----	-----	.00165
	65,000	<sup>b</sup> 125	.274	-----	-----	-----	.0035

<sup>a</sup>Minimum rates of tests entering third-stage creep.<sup>b</sup>Time of transition to third-stage creep.<sup>c</sup>W.Q. - Water-quenched.

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TABLE XVII.- CREEP DATA AT 1200°, 1350°, AND 1500° F FOR LOW-CARBON

M-155 ALLOY BAR STOCK FROM HEAT A1726

Treatment	Stress (psi)	Duration (hr)	Initial deformation (percent)	Creep rate (percent/hr) at -			
				500 hr	1000 hr	1500 hr	Minimum*
1200° F							
As-rolled	15,000	1680	0.0550	0.000023	0.000023	0.000023	
	20,000	1534	.0905	.000099	.000080	.000051	
	25,000	690	.1162	.000175			
	30,000	1586	.1273	.00039	.000250	.00025	
	32,500	863	.1432	.00093			
	42,000	b375					0.0081
	45,000	b190	.196				.0137
	47,000	b115					.0270
2100° F, 1 hr, W.Q. <sup>c</sup>	27,500	1238	0.120	0.000700	0.000390		
	30,000	1268	.160	.000850	.000470		
	32,500	1238	.225	.000930	.000560		
	35,000	982	.320	.00168	.00137		
	37,000	b920	.430				0.00225
	40,000	b720	.670				.00480
2200° F, 1 hr, W.Q. + aged 24 hr at 1400° F	25,000	1675	0.1125	0.00025	0.00025	0.00025	
	30,000	b1150	.1365	.00114	.00114	.00156	.00114
	34,000	b95	.1759	.00500			
	44,000	b265	.636				.0120
	46,000	b94	.732				.0360
2050° F, 2 hr, W.Q. + 15% hot-cold-work at 1200° F	30,000	1458	0.1360	0.000033	0.000033	0.000033	
	37,000	1310	.1680	.000092	.000092		
	42,000	297	.1900				0.000332
	48,000		.217				.00075
	49,000		.222				.00070
	52,000	b220	.225				.00136
	55,000		.249				.00200
1350° F							
As-rolled	10,000	1657	0.0467	0.000096	0.000054	0.000030	
	15,000	1651	.0769	.000200	.000111	.000056	
	20,000	1567	.0957	.000492	.000357	.000357	
	30,000	b335	.1810				0.0082
	32,500	b89	.240				.0690
2100° F, 1 hr, W.Q.	12,500	1464	0.0530	0.000185	0.000072	0.000037	
	15,000	1274	.0630	.000325	.000137		
	17,500	1464	.0740	.000378	.000195	.000195	
	20,000	1268	.0850	.001075	.000750		
	25,000	b405	.095				0.0138
	27,000	b220	.112				.0380
	29,000	b95	.135				.0540
	30,000	b65	.153				.0730
2200° F, 1 hr, W.Q. + aged 24 hr at 1400° F	10,000	1657	0.0483	0.000095	0.000020	0.000020	
	15,000	1483	.0731	.000197	.000064	.000048	
	17,500	1315	.0781	.000303	.000135	.000065	
	20,000	864	.1024	.000760	.000690		
	26,000	b270					0.0290
	30,000	b90					.0510
2050° F, 2 hr, W.Q. + 15% hot-cold-work at 1200° F	15,000	1561	0.0680	0.000089	0.000048	0.000048	
	20,000	1127	.0910	.000133	.000133		
	22,500	1555	.1030	.000123	.000123	.000123	
	25,000	b410	.1160	.000343	.000343	.000370	0.000343
	33,000	b312	.149				.0025
	36,000	b195	.162				.0037
	38,000	b92	.175				.0090
1500° F							
As-rolled	7,500	1215	0.0340	0.000106	0.000058		
	9,000	b1225	.0442	.000200	.000200		0.000200
	10,500	450	.0564	.000400			
	12,000	b400	.0580				.0032
	13,000	b110	.0630				.0120
	13,500	b260	.0680				.0140
	15,000	b72	.0790				.0600
2100° F, 1 hr, W.Q.	8,500	1152	0.0409	0.000086	0.000013		
	10,000	1278	.0433	.000063	.000025		
	12,000	b410	.0546	.00059			0.000446
	15,000	b234	.181				.0114
	16,500	b136	.240				.0560
2200° F, 1 hr, W.Q. + aged 24 hr at 1400° F	7,000	1483	0.0328	0.000028	0.000019	0.000010	
	9,000	b1250	.0422	.000084	.000052	.000077	0.000052
	10,000	b500	.0552	.000069	.000105		.000069
	12,000	b310	.0571	.000785	.00494		.000350
	14,500	b330	.0695				.00210
	16,000	b140	.0763				.00390
	18,000	b95	.0857				.0274
2050° F, 2 hr, W.Q. + 15% hot-cold-work at 1200° F	10,000	1119	0.0515	0.000101	0.000081		
	11,500	1000	.0747	.000132	.000089		
	12,500	1274	.0995	.000099	.000074		
	18,000	b424	.116				0.00290
	20,000	b143	.134				.00625

\*Minimum rates of tests entering third-stage creep.

<sup>b</sup>Time for transition to third-stage creep.<sup>c</sup>W.Q. - Water-quenched.

TABLE XVIII.- CREEP STRENGTHS OF TWO HEATS OF LOW-CARBON

N-155 ALLOY BAR STOCK

Treatment (a)	Heat	Temperature (°F)	Creep strengths (psi) from tests at -			
			0.00001 percent/hr		0.0001 percent/hr	
			1000 hr	1500 hr	1000 hr	1500 hr
As-rolled	30276	1200	8,200	-----	15,500	23,000
As-rolled	A1726	1200	11,800	11,800	23,000	
ST(2100)	A1726	1200	-----	-----	-----	
ST+Ag(1350)	30276	1200	13,700	-----	20,800	22,000
ST+Ag(1400)	A1726	1200	-----	-----	-----	
ST+15%HCW	A1726	1200	23,500	23,500	37,000	
ST+25%HCW	30276	1200	15,500	-----	34,000	<sup>b</sup> 37,000
As-rolled	A1726	1350	<sup>b</sup> 4,000	<sup>b</sup> 5,000	14,000	16,000
ST(2100)	A1726	1350	-----	<sup>b</sup> 9,500	14,000	15,000
ST+Ag(1400)	A1726	1350	8,000	8,000	16,000	17,500
ST+15%HCW	A1726	1350	<sup>b</sup> 8,400	<sup>b</sup> 8,400	19,500	19,500
As-rolled	A1726	1500	-----	-----	8,200	
ST(2100)	A1726	1500	8,000	-----	11,000	
ST+Ag(1400)	A1726	1500	5,800	7,000	10,000	
ST+15%HCW	A1726	1500	-----	-----	11,000	

<sup>a</sup>Treatments: ST(2100) - 2100° F, 1 hr, water-quenched.  
 ST+Ag(1350) - 2200° F, 1 hr, water-quenched; 1350° F, 50 hr.  
 ST+Ag(1400) - 2200° F, 1 hr, water-quenched; 1400° F, 24 hr.  
 ST+15%HCW - 2050° F, 2 hr, water-quenched; 15% hot-cold-work at 1200° F.  
 ST+25%HCW - 2050° F, 2 hr, water-quenched; 25% hot-cold-work at 1200° F.

<sup>b</sup>Estimated.

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TABLE XIX.- COMPARATIVE CREEP AND RUPTURE STRENGTHS OF  
LOW-CARBON N-155 ALLOY BAR STOCK

Treatment	Heat	Temperature (°F)	Creep strength, 0.0001 percent/hr (psi)	Rupture strength, 10,000 hr (psi)
As-rolled	30276	1200	15,500	28,000
As-rolled	A1726	1200	23,000	38,000
2100° F, 1 hr, W.Q. <sup>a</sup>	A1726	1200	<sup>b</sup> 15,000	34,000
2200° F, 1 hr, W.Q. + aged 1350° F for 50 hr	30276	1200	20,800	32,000
2200° F, 1 hr, W.Q. + aged 1400° F for 24 hr	A1726	1200	22,000	38,000
2050° F, 2 hr, W.Q. + 15% hot-cold-work	A1726	1200	37,000	42,000
2050° F, 2 hr, W.Q. + 25% hot-cold-work	30276	1200	34,000	45,000
As-rolled	A1726	1350	14,000	24,000
2100° F, 1 hr, W.Q.	A1726	1350	14,000	20,000
2200° F, 1 hr, W.Q. + aged 24 hr at 1400° F	A1726	1350	16,000	20,000
2050° F, 2 hr, W.Q. + 15% hot-cold-work	A1726	1350	19,500	23,000
As-rolled	A1726	1500	8,200	8,600
2100° F, 1 hr, W.Q.	A1726	1500	11,000	11,500
2200° F, 1 hr, W.Q. + aged 24 hr at 1400° F	A1726	1500	10,000	10,000
2050° F, 2 hr, W.Q. + 15% hot-cold-work	A1726	1500	11,000	12,000

<sup>a</sup>W.Q. - Water-quenched.

<sup>b</sup>Estimated.



TABLE XX. - EFFECT OF CREEP TESTING AT 1200°, 1350°, AND 1500° F ON PHYSICAL PROPERTIES

AT ROOM TEMPERATURE OF LOW-CARBON N-155 ALLOY BAR STOCK FROM HEAT A1726

Treatment	Testing conditions			Tensile strength (psi)	Offset yield strength (psi)			Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Izod impact strength (ft-lb)	Vickers hardness
	Temperature (°F)	Stress (psi)	Time (hr)		0.02 percent	0.1 percent	0.2 percent					
As-rolled		Original		127,200	63,000	73,200	77,400	46,500	40	51	101, 97	249
	1200	15,000	1680	129,000	65,300	75,800	79,800	53,000	34	38.5	-----	---
	1200	32,500	863	-----	-----	-----	-----	-----	-----	-----	26, 26	282
	1350	10,000	1657	131,000	62,200	75,700	79,200	43,500	18	16	-----	---
	1350	20,000	1567	-----	-----	-----	-----	-----	-----	-----	8, 8	282
	1500	7,500	1215	128,000	53,000	64,800	70,100	39,500	27	27.5	-----	---
	1500	10,500	450	-----	-----	-----	-----	-----	-----	-----	12, 12	261
2100° F, 1 hr, W.Q. <sup>1</sup>		Original		117,000	45,700	52,800	56,300	36,000	50	67.6	116, 115	201
	1200	27,500	1238	127,000	66,000	72,100	74,700	55,500	33.5	36	-----	---
	1200	30,000	1268	-----	-----	-----	-----	-----	-----	-----	33, 35	258
	1350	12,500	1464	137,500	61,500	70,000	74,700	50,000	14.5	12.5	-----	---
	1350	20,000	1268	-----	-----	-----	-----	-----	-----	-----	11, 11	280
	1500	8,500	1152	115,000	43,700	53,700	58,800	33,000	11.5	10.8	-----	---
	1500	12,000	1100	-----	-----	-----	-----	-----	-----	-----	15, 18	233
2200° F, 1 hr, W.Q. + aged 24 hr at 1400° F		Original		118,900	47,800	55,800	59,400	37,000	38	46.8	33, 33	231
	1200	25,000	1675	125,500	60,400	68,400	71,800	52,000	21	18.5	-----	---
	1200	34,000	495	-----	-----	-----	-----	-----	-----	-----	8, 8	263
	1350	10,000	1484	130,000	56,700	69,500	74,700	39,500	13.5	11.7	-----	---
	1350	20,000	864	-----	-----	-----	-----	-----	-----	-----	4, 4	282
	1500	7,000	1483	116,000	49,300	59,100	64,200	38,000	13	10	-----	---
	1500	12,000	1079	-----	-----	-----	-----	-----	-----	-----	6, 7	251
2050° F, 2 hr, W.Q. + 15% hot-cold-work at 1200° F		Original		144,000	107,500	117,200	120,300	97,500	24	57.0	76, 71	313
	1200	30,000	1458	141,000	97,700	108,700	113,000	85,000	20.5	33.8	-----	---
	1200	37,000	1310	-----	-----	-----	-----	-----	-----	-----	-----	313
	1350	15,000	1561	136,500	75,000	88,200	93,900	58,000	8	13.5	-----	---
	1350	25,000	1639	-----	-----	-----	-----	-----	-----	-----	3, 5	292
	1500	10,000	1119	127,500	64,000	77,200	83,700	46,000	14.5	15.6	-----	---
	1500	11,500	1000	-----	-----	-----	-----	-----	-----	-----	8, 8	261

<sup>1</sup>W.Q. - Water-quenched.

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TABLE XXI.- LOW-ANGLE X-RAY DIFFRACTION PATTERNS FROM RUPTURE SPECIMENS OF SOLUTION-TREATED

AND HOT-COLD-WORKED 25-PERCENT LOW-CARBON N-155 ALLOY FROM HEAT 30276

[Cr K $\alpha$  radiation]

Diffraction patterns from rupture specimens of low-carbon N-155 alloy				Standard diffraction patterns				Indicated phase in low-carbon N-155
1500° F - 13,000 psi - 340 hr		1350° F - 30,000 psi - 446 hr		Sigma phase (reference 4)		CbC (reference 5)		
d (Å)	Intensity (1)	d (Å)	Intensity (1)	d (Å)	Intensity (1)	d (Å)	Intensity (1)	
2.52	M	2.54	M	-----	--	2.54	S	CbC
-----	---	-----	---	2.50	VW			
-----	---	-----	---	2.360	VW			
-----	---	-----	---	2.323	VW			
-----	---	-----	---	2.268	VW			
2.182	W	2.21	VW	-----	--	2.20	S	CbC
2.12	W(M)	2.14	M	2.115	S			Sigma
-----	---	-----	---	2.067	M			
-----	---	-----	---	2.034	VW			
2.015	W	-----	---	2.020	M			Sigma
1.965	W	1.97	W	1.968	M			Sigma
1.92	W	1.94	W	1.926	S			Sigma
1.89	W	-----	---	1.882	M			Sigma
-----	---	-----	---	1.836	W			
-----	---	-----	---	1.762	VW			
1.556	S	1.56	M	-----	--	1.55	S	CbC
1.32	S	1.327	M	1.326	M	1.33	M	CbC and Sigma
-----	---	-----	---	1.295	VW			
1.248	W	-----	---	1.256	M			Sigma
-----	---	-----	---	1.240	VW			
1.23	W	-----	---	1.235	M			Sigma
-----	---	-----	---	1.229	W			
1.221	W	-----	---	1.224	W(M)			Sigma
1.21	W	-----	---	1.218	W(M)			Sigma
1.20	W	-----	---	1.205	M			Sigma
-----	---	-----	---	1.198	M			
-----	---	-----	---	1.186	W			
-----	---	-----	---	1.175	W(M)			
1.176	M(S)	-----	---	1.166	M(S)			Sigma

1 M, medium; W, weak; S, strong; V, very.



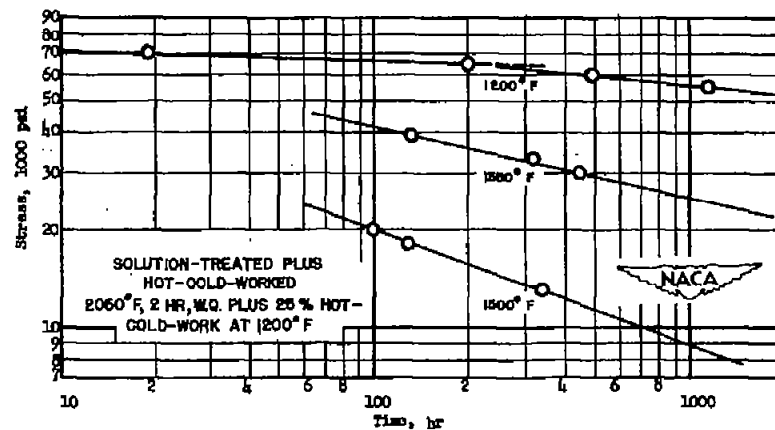
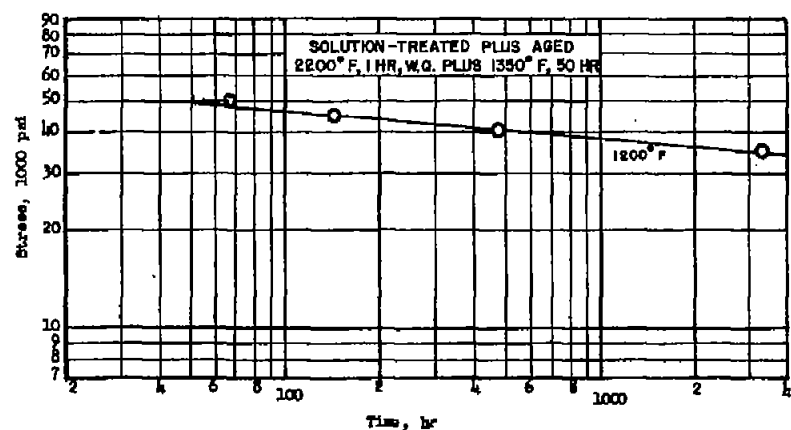
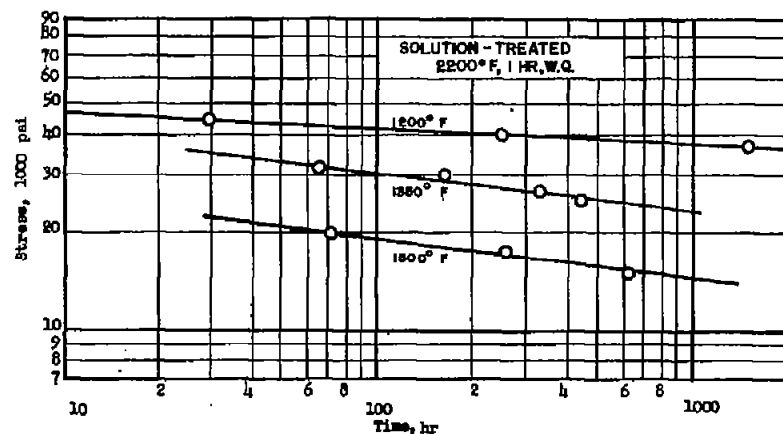
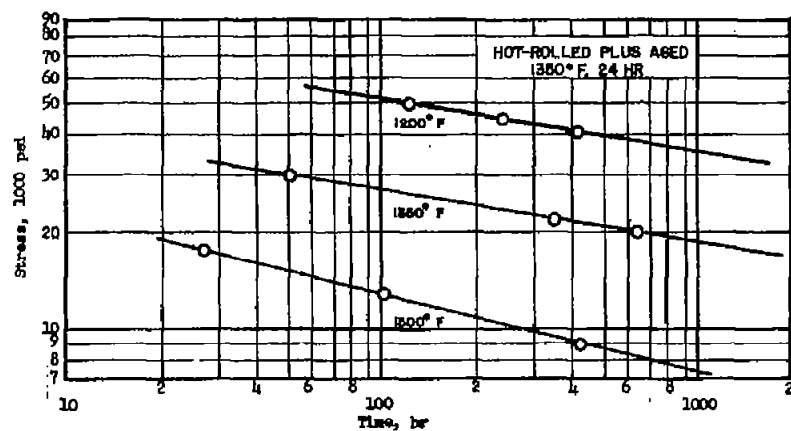
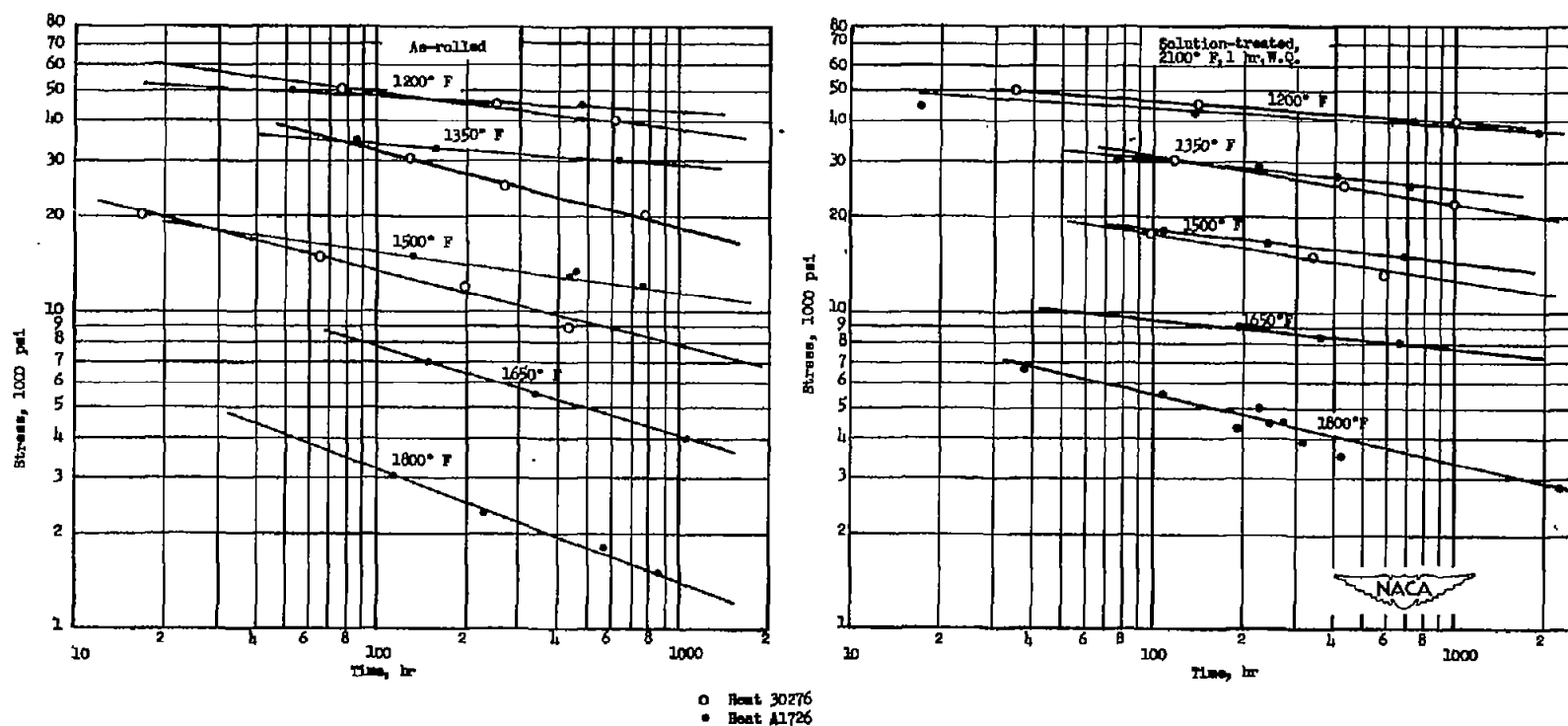
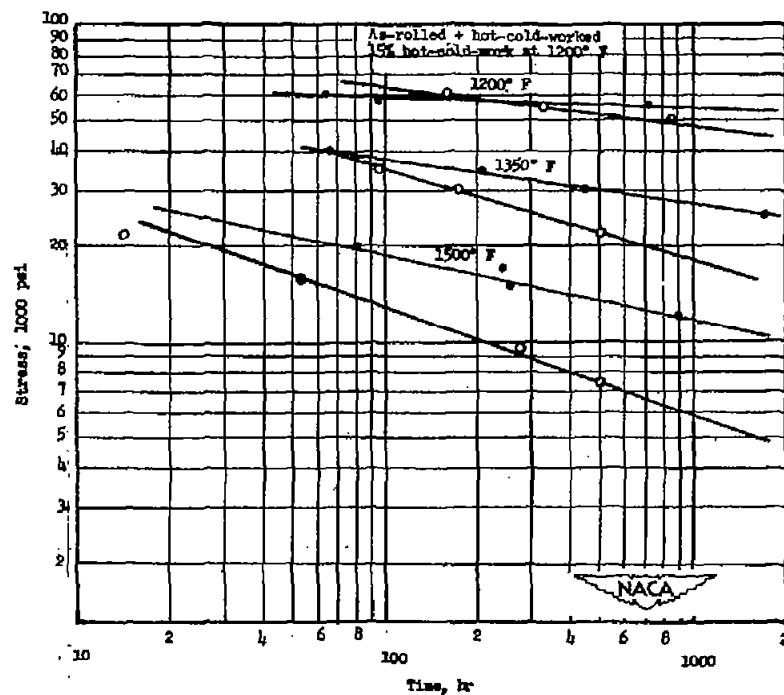
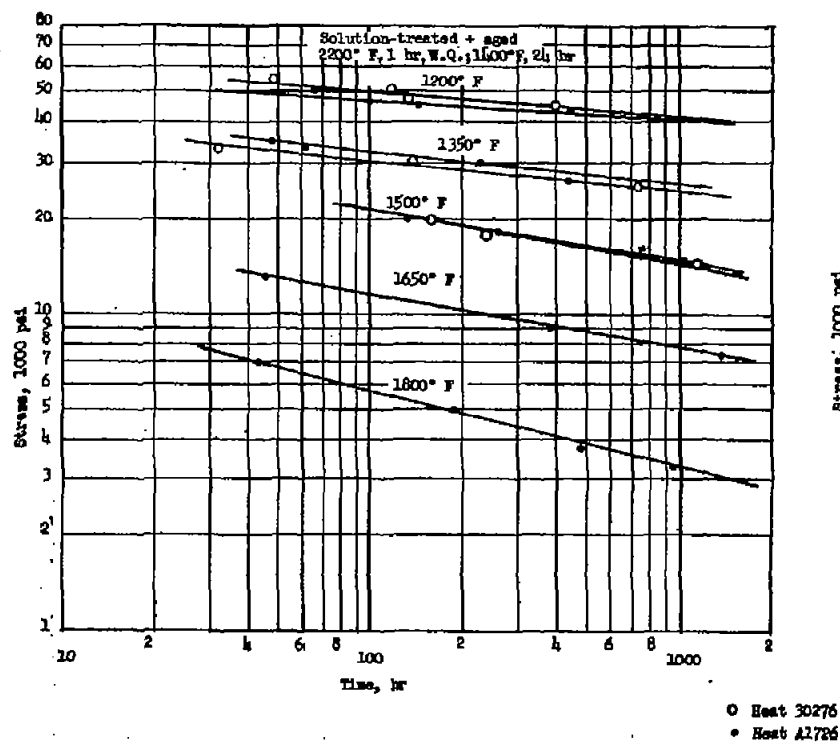


Figure 1.- Curves of stress against rupture time at 1200°, 1350°, and 1500° F for low-carbon N-155 alloy bar stock from heat 30276.



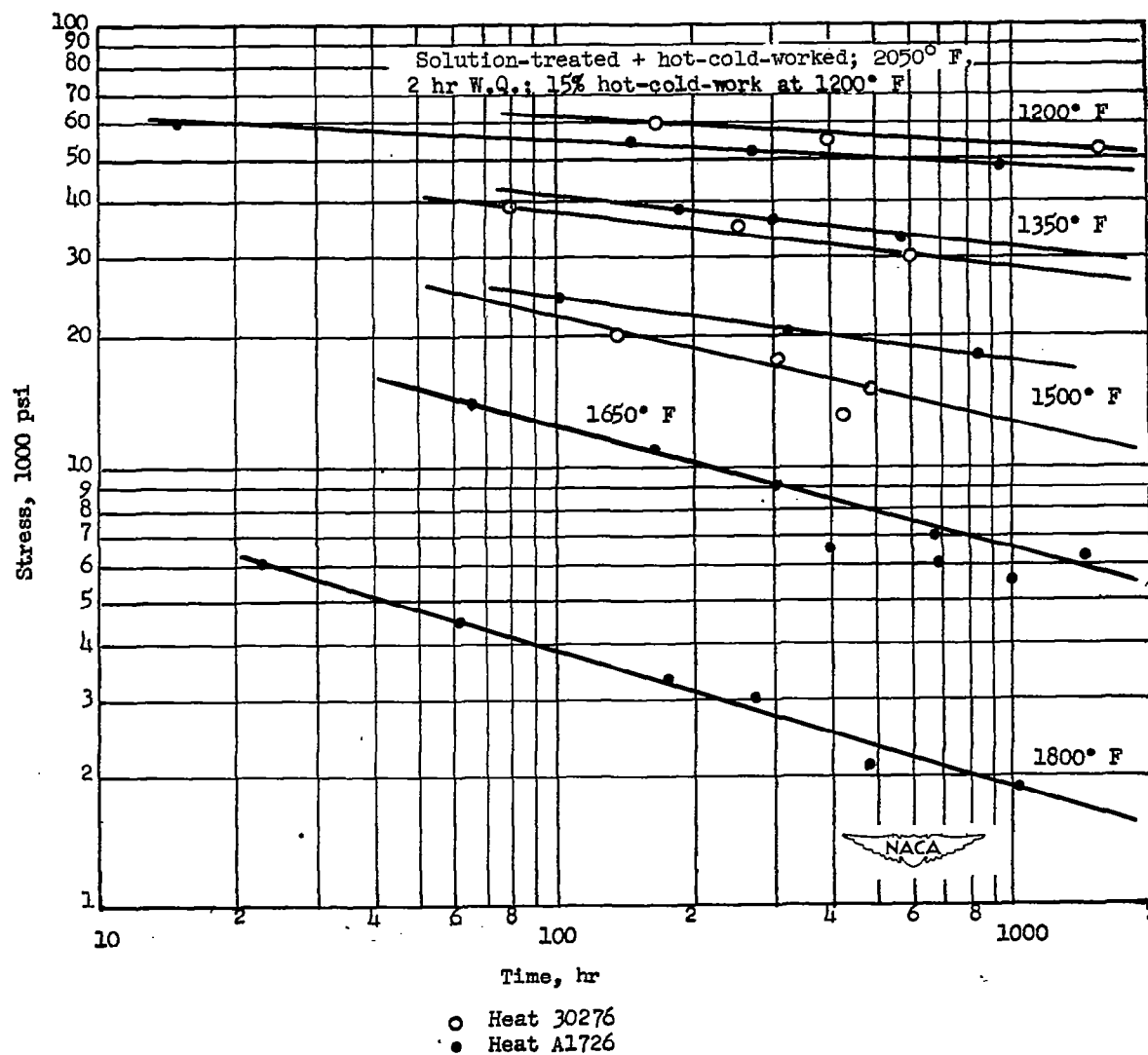
(a) As-rolled and solution-treated conditions.

Figure 2.- Curves of stress against rupture time at 1200° to 1800° F for low-carbon N-155 alloy bar stock from two heats.



(b) Solution-treated plus aged and as-rolled plus hot-cold-worked conditions.

Figure 2.- Continued.



(c) Solution-treated plus hot-cold-worked condition.

Figure 2.- Concluded.

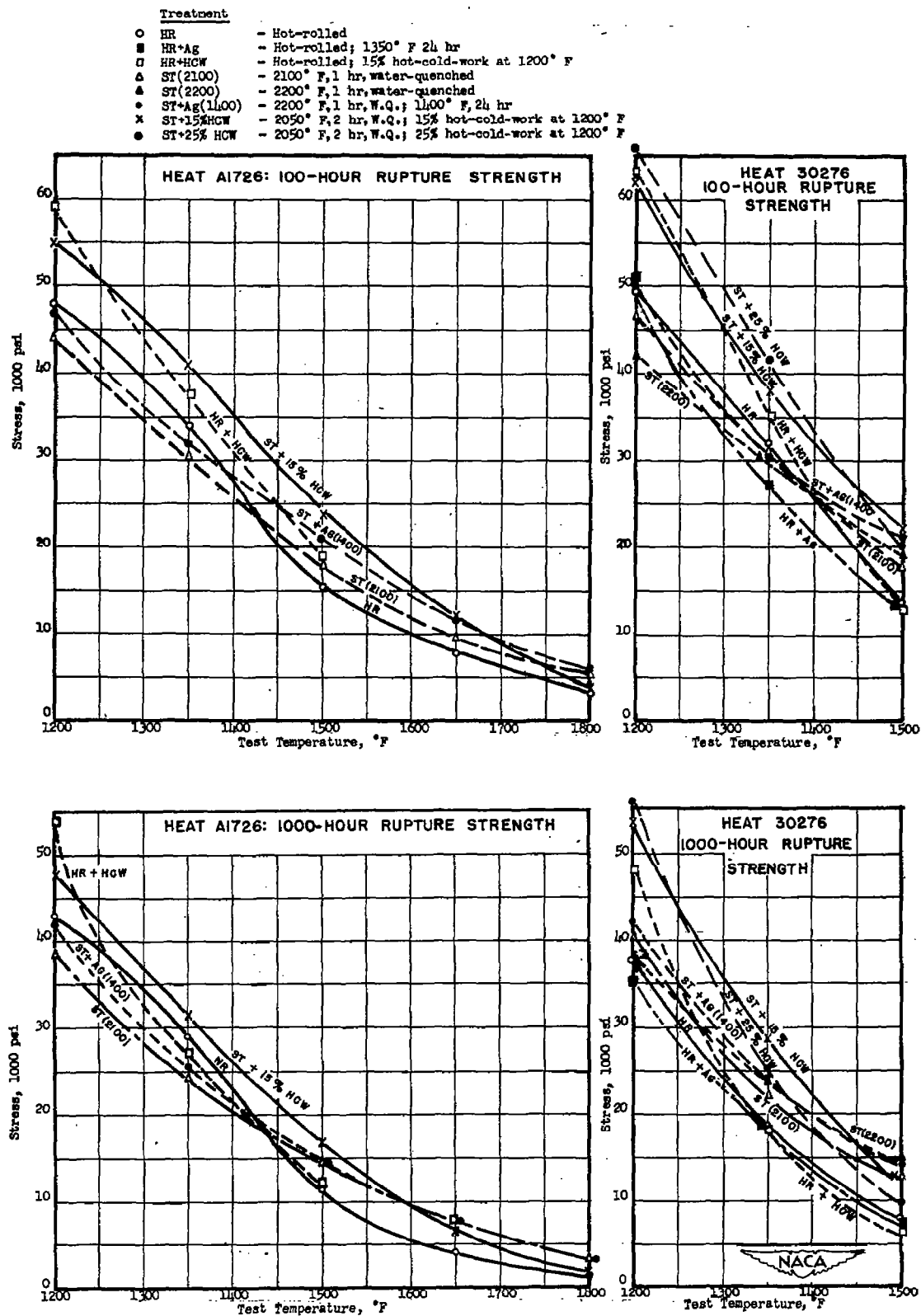


Figure 3.- Influence of testing temperature on rupture strength of low-carbon N-155 alloy bar stock from two heats.

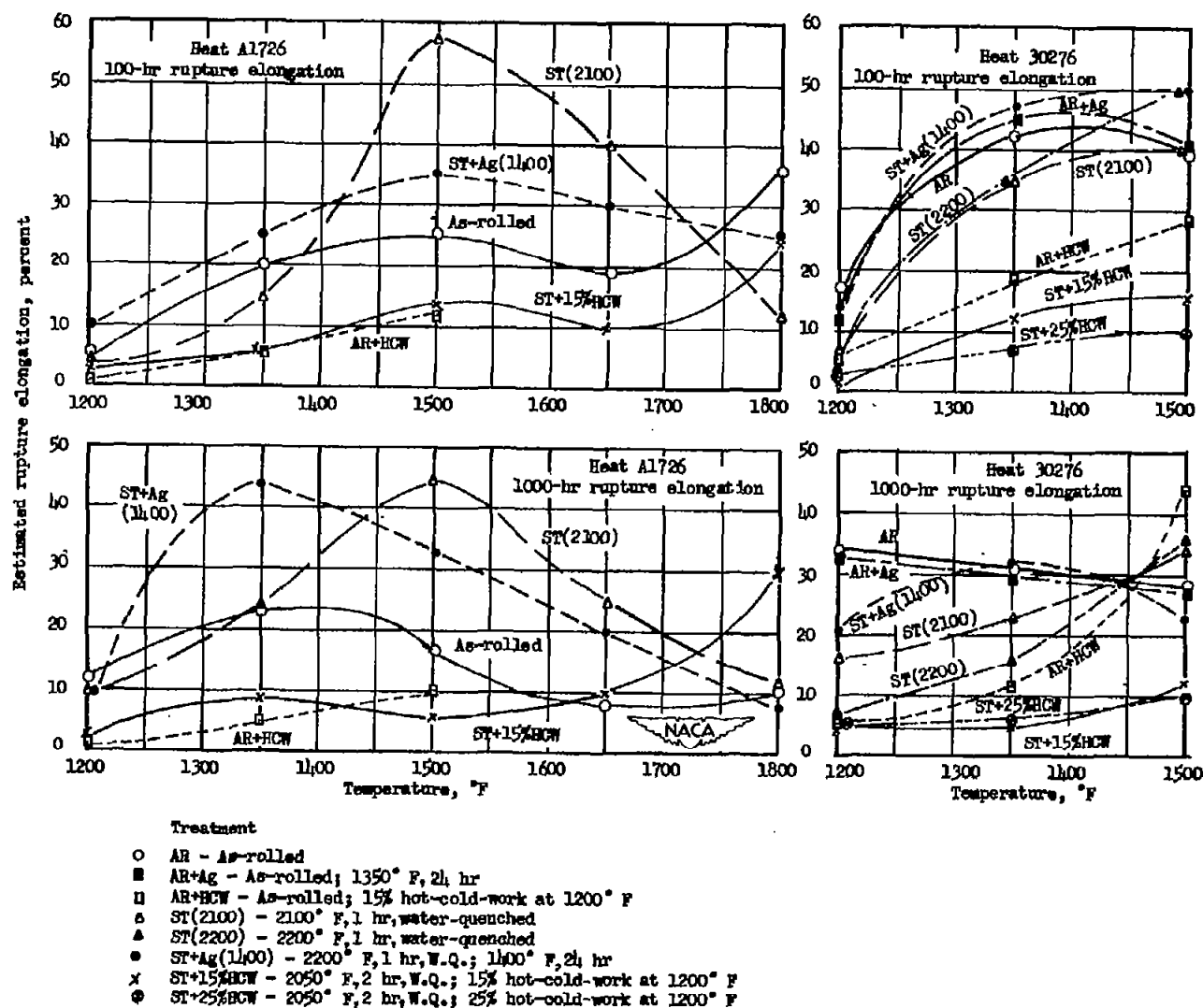


Figure 4.- Influence of testing temperature on rupture elongation of low-carbon N-155 alloy bar stock from two heats.

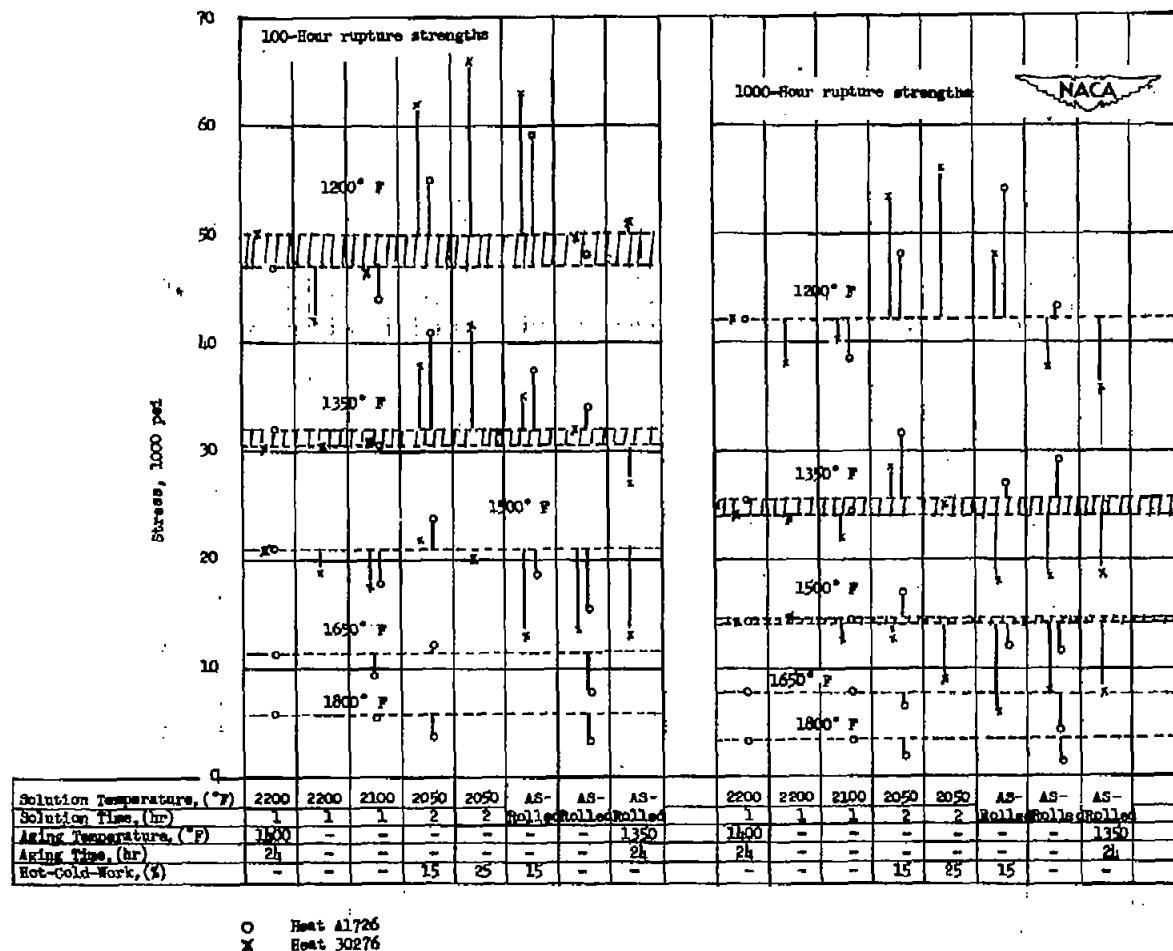


Figure 5.- Rupture strengths of variously treated low-carbon N-155 bar stock compared with rupture strengths of solution-treated and aged condition. Horizontal dashed lines indicate range of properties for the two heats in the solution-treated and aged condition (2200° F, 1 hr, water-quenched; 1400° F, 24 hr).

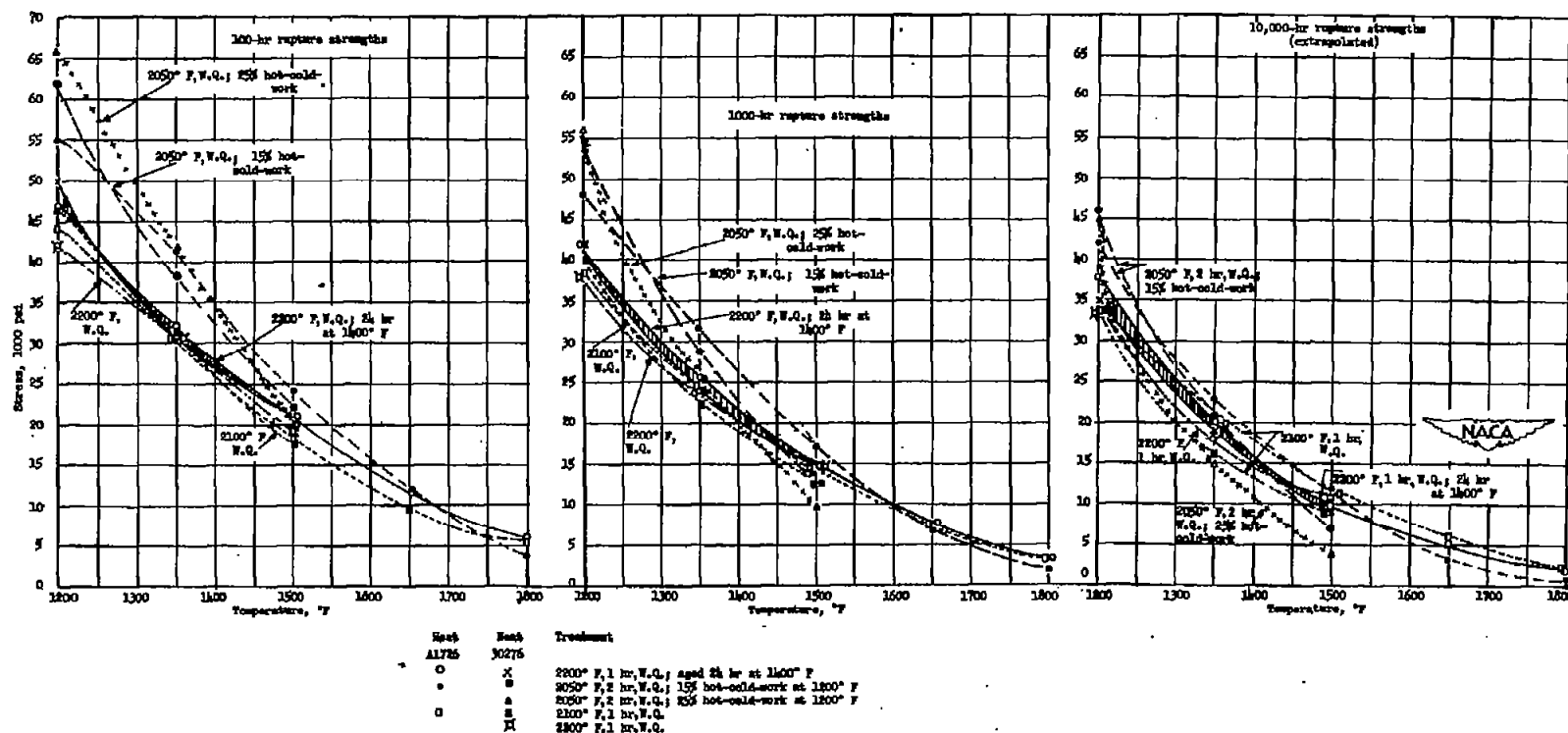


Figure 6.- Influence of temperature on relative rupture strengths of solution-treated and aged, solution-treated and hot-cold-worked, and solution-treated low-carbon N-155 alloy bar stock. Shaded area indicates property ranges for two heats in solution-treated and aged condition (2200° F, 1 hr, water-quenched; 1400° F, 24 hr).

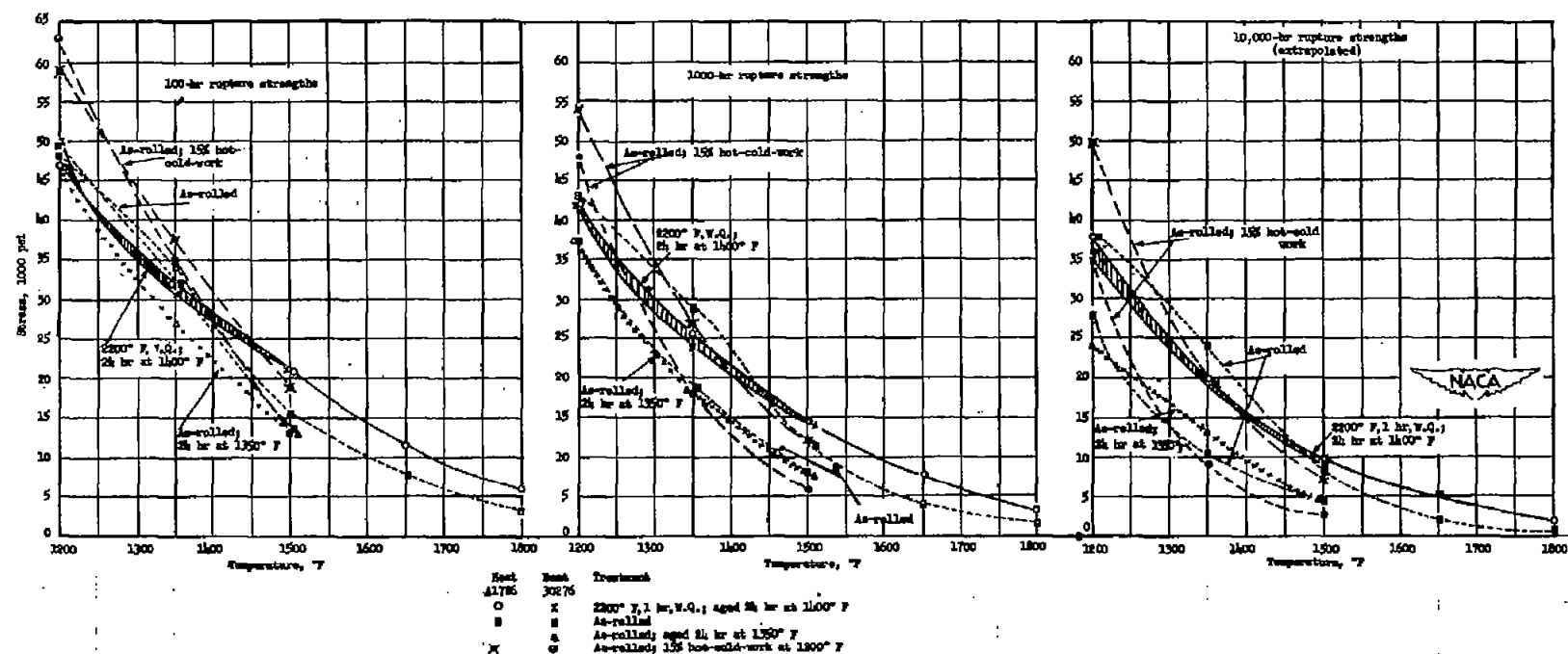
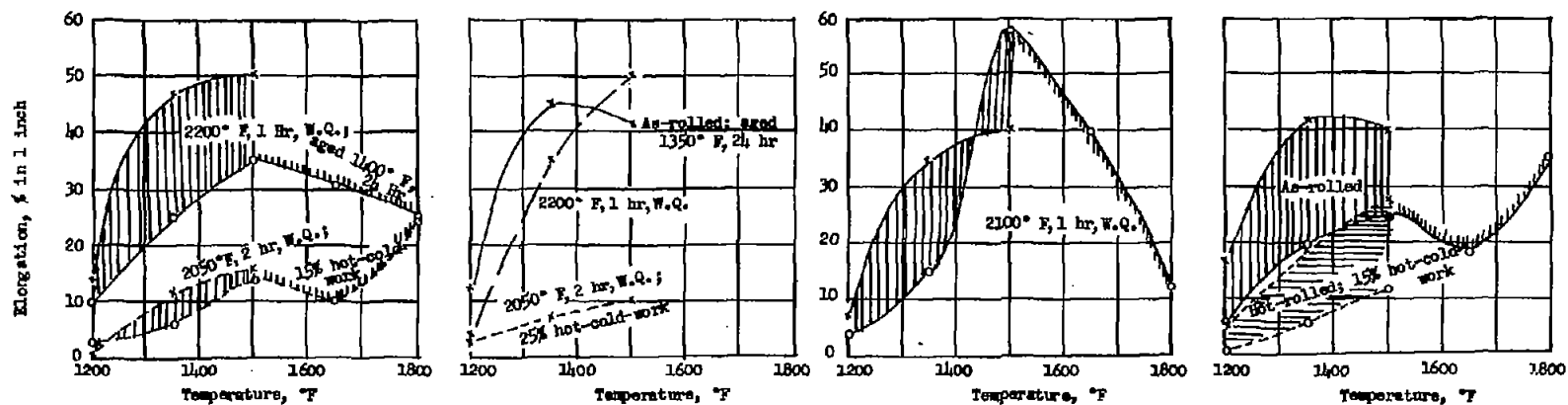
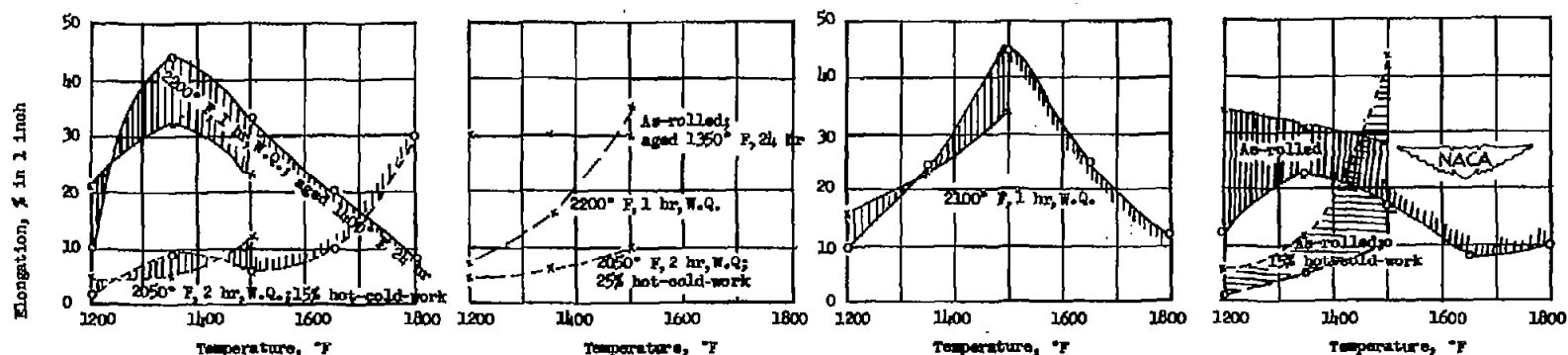


Figure 7.- Influence of temperature on relative rupture strengths of solution-treated and aged, as-rolled, as-rolled and aged, and as-rolled and hot-cold-worked low-carbon N-155 alloy bar stock. Shaded area indicates property ranges for two heats in solution-treated and aged condition (2200° F, 1 hr, water-quenched; 1400° F, 24 hr).



(a) Estimated elongation for rupture in 100 hours.



o Heat A1726  
x Heat 30276

(b) Estimated elongation for rupture in 1000 hours.

Figure 8.- Influence of testing temperature and prior treatment on rupture elongations of low-carbon N-155 alloy bar stock from two heats.

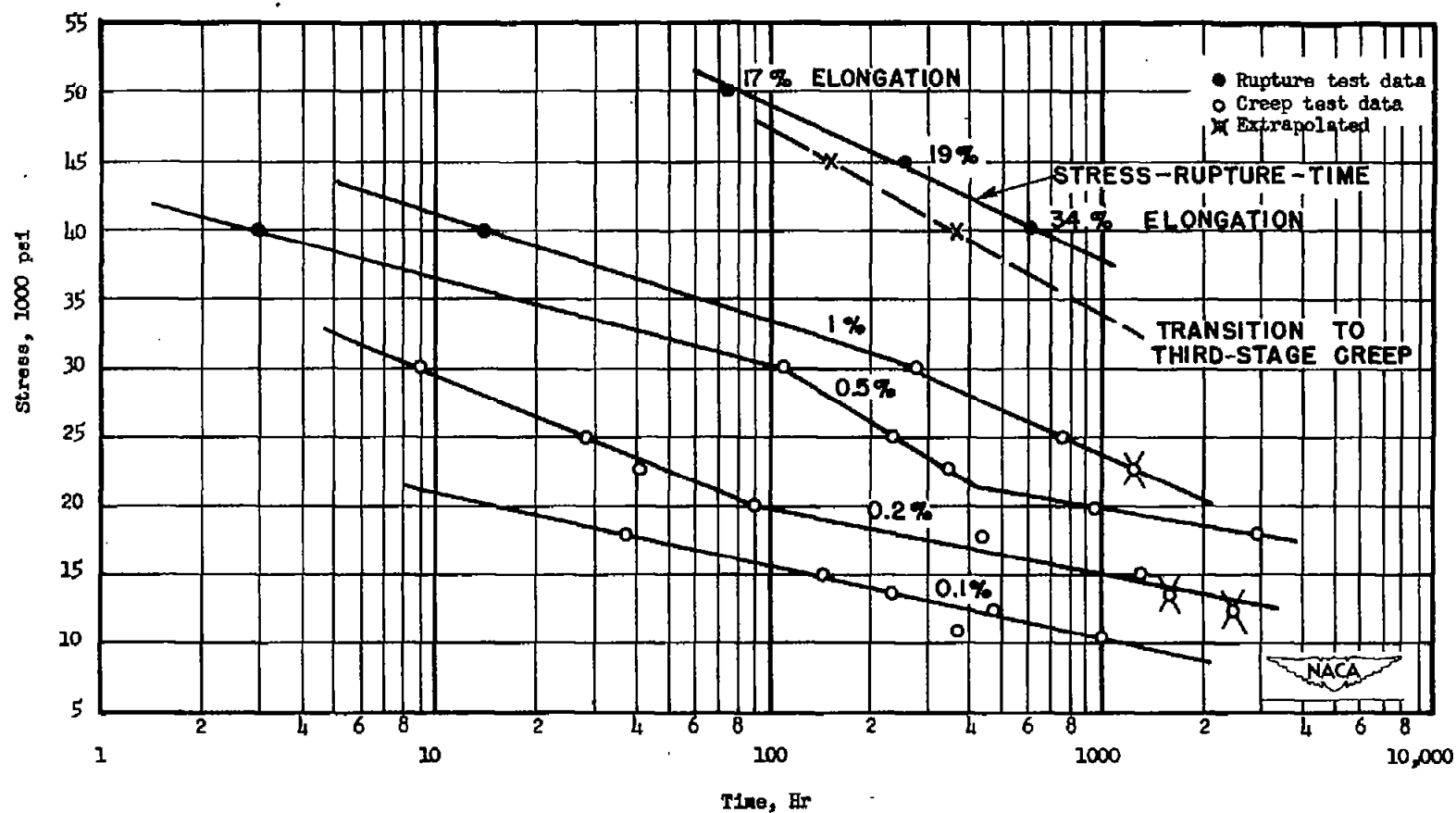


Figure 9.- Curves of stress against time for total deformation at 1200° F for hot-rolled low-carbon N-155 alloy bar stock from heat 30276.

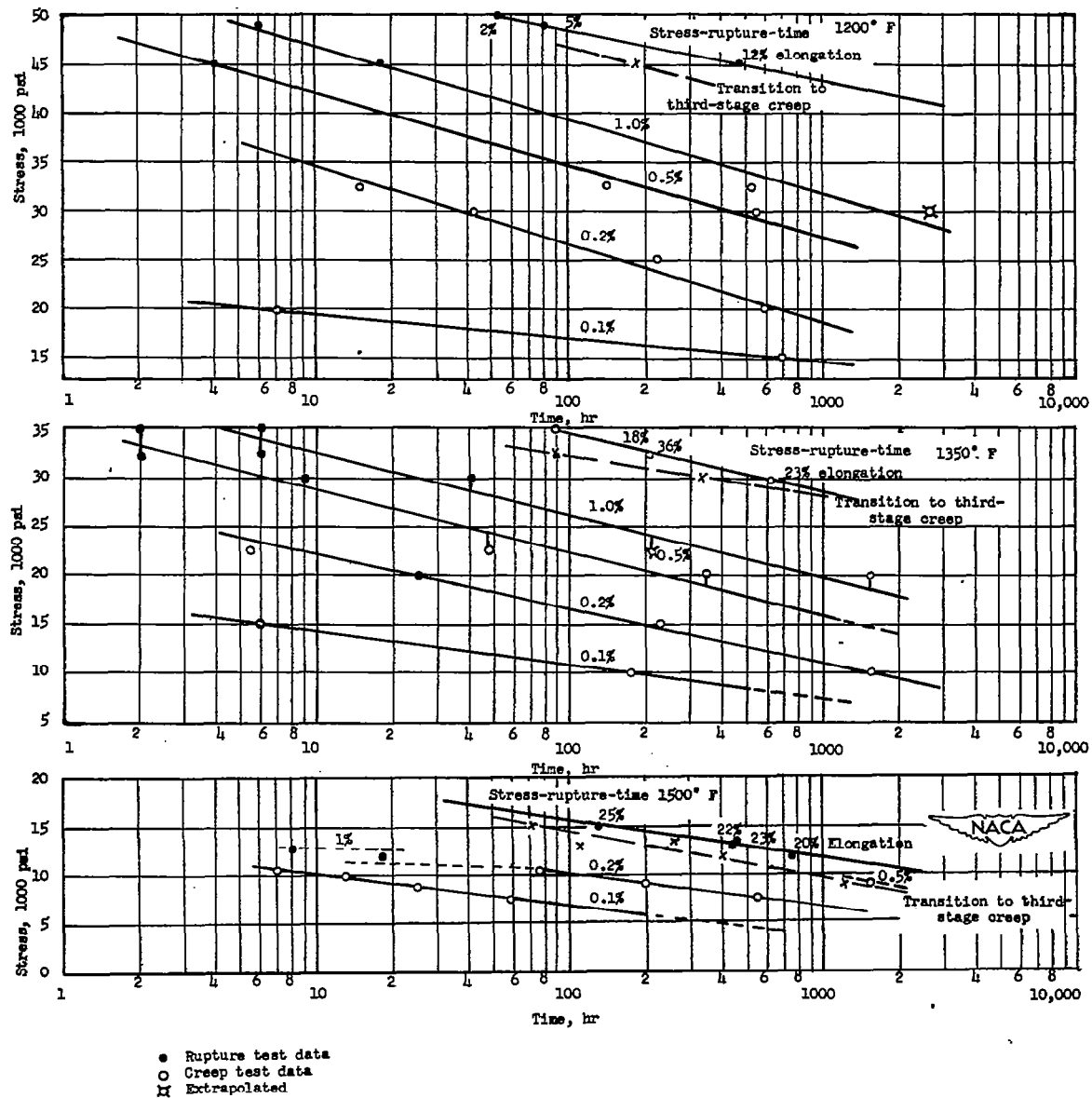


Figure 10.- Curves of stress against time for total deformation at 1200°, 1350°, and 1500° F for hot-rolled low-carbon N-155 alloy bar stock from heat A1726.

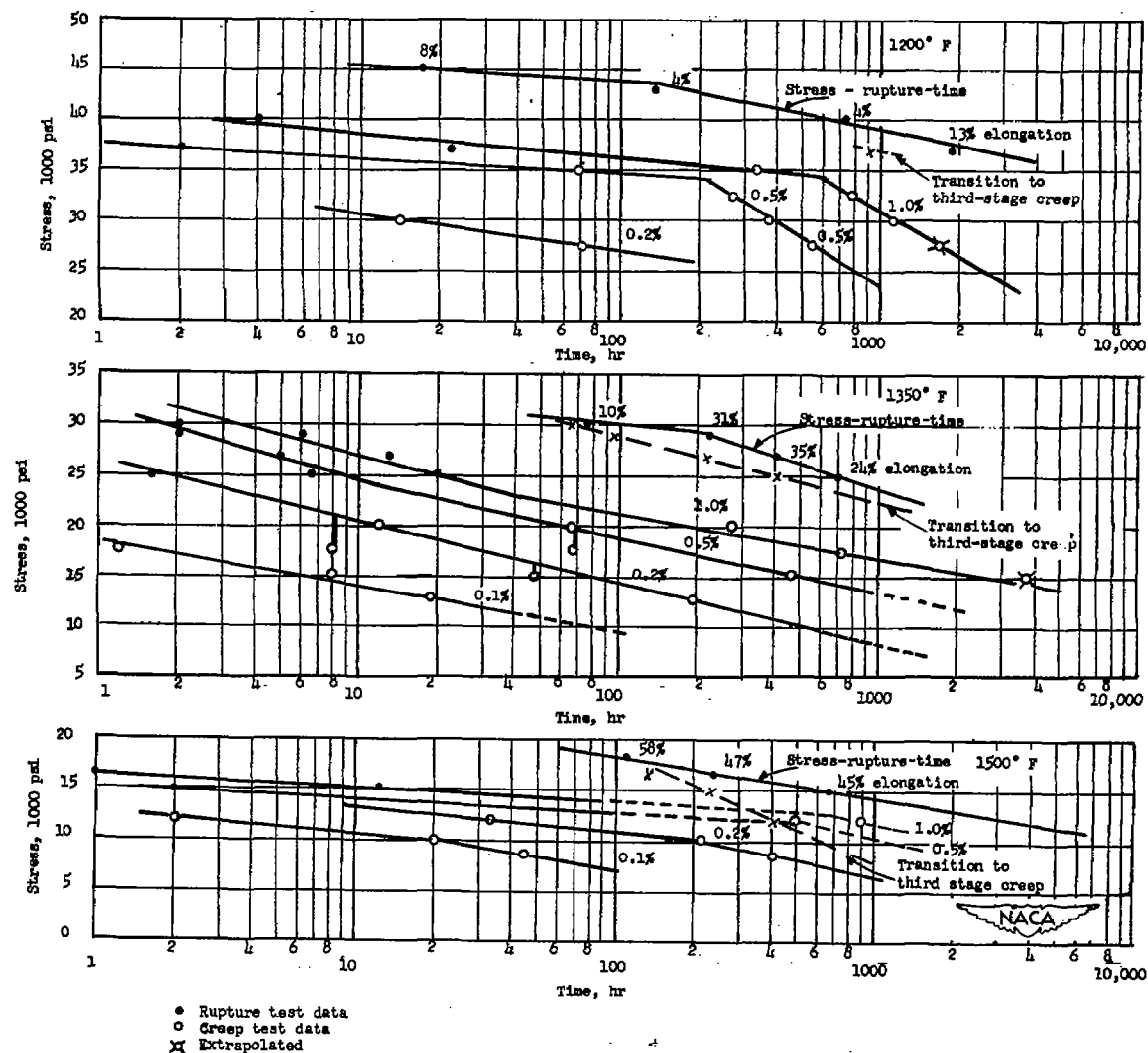


Figure 11.- Curves of stress against time for total deformation at 1200°, 1350°, and 1500° F for solution-treated low-carbon N-155 alloy bar stock from heat A1726. (Treatment: 2100° F, 1 hr, water-quenched.)

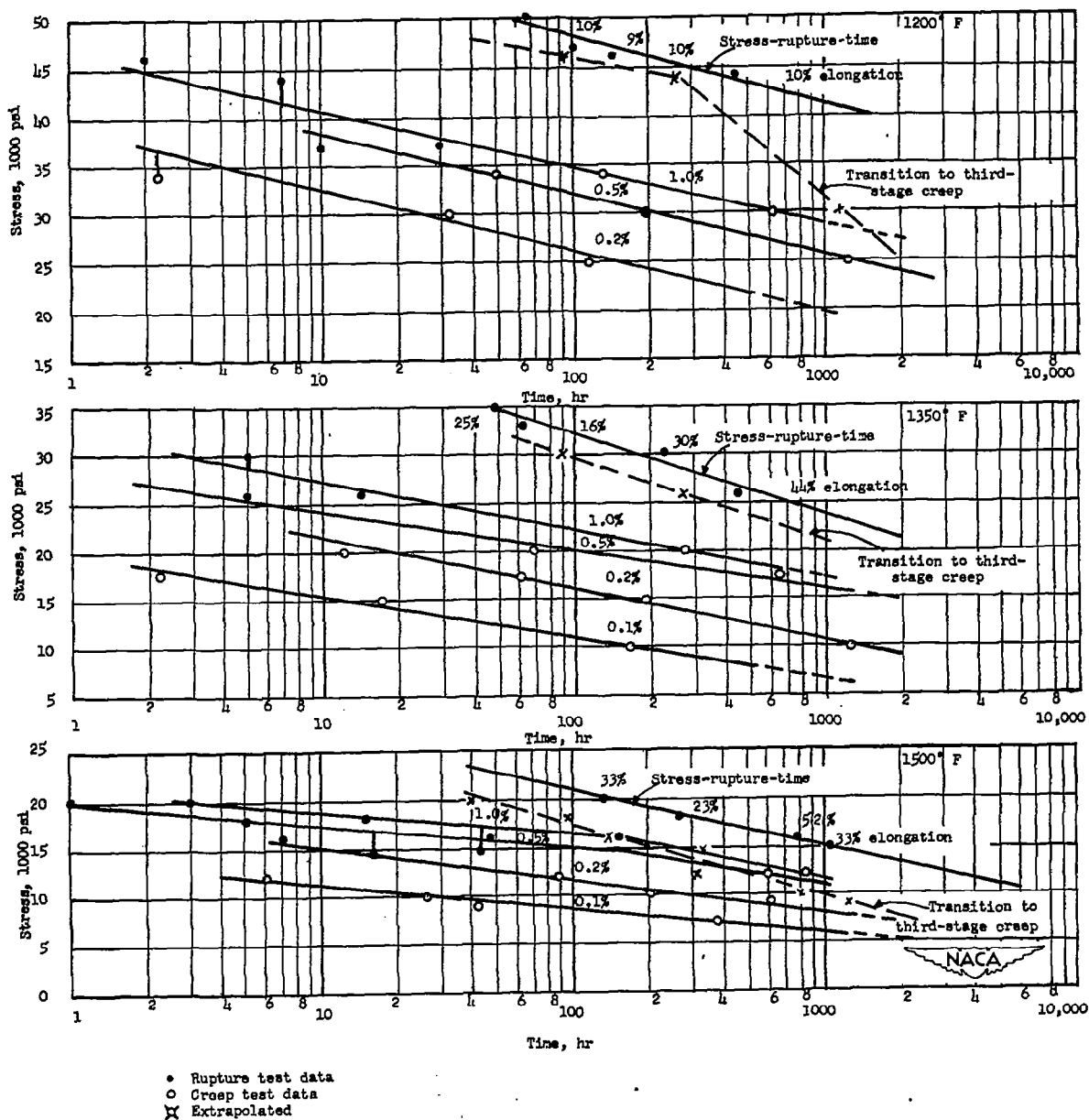


Figure 12.- Curves of stress against time for total deformation at 1200°, 1350°, and 1500° F for solution-treated and aged low-carbon N-155 alloy bar stock from heat A1726. (Treatment: 2200° F, 1 hr, water-quenched; 1400° F, 24 hr.)

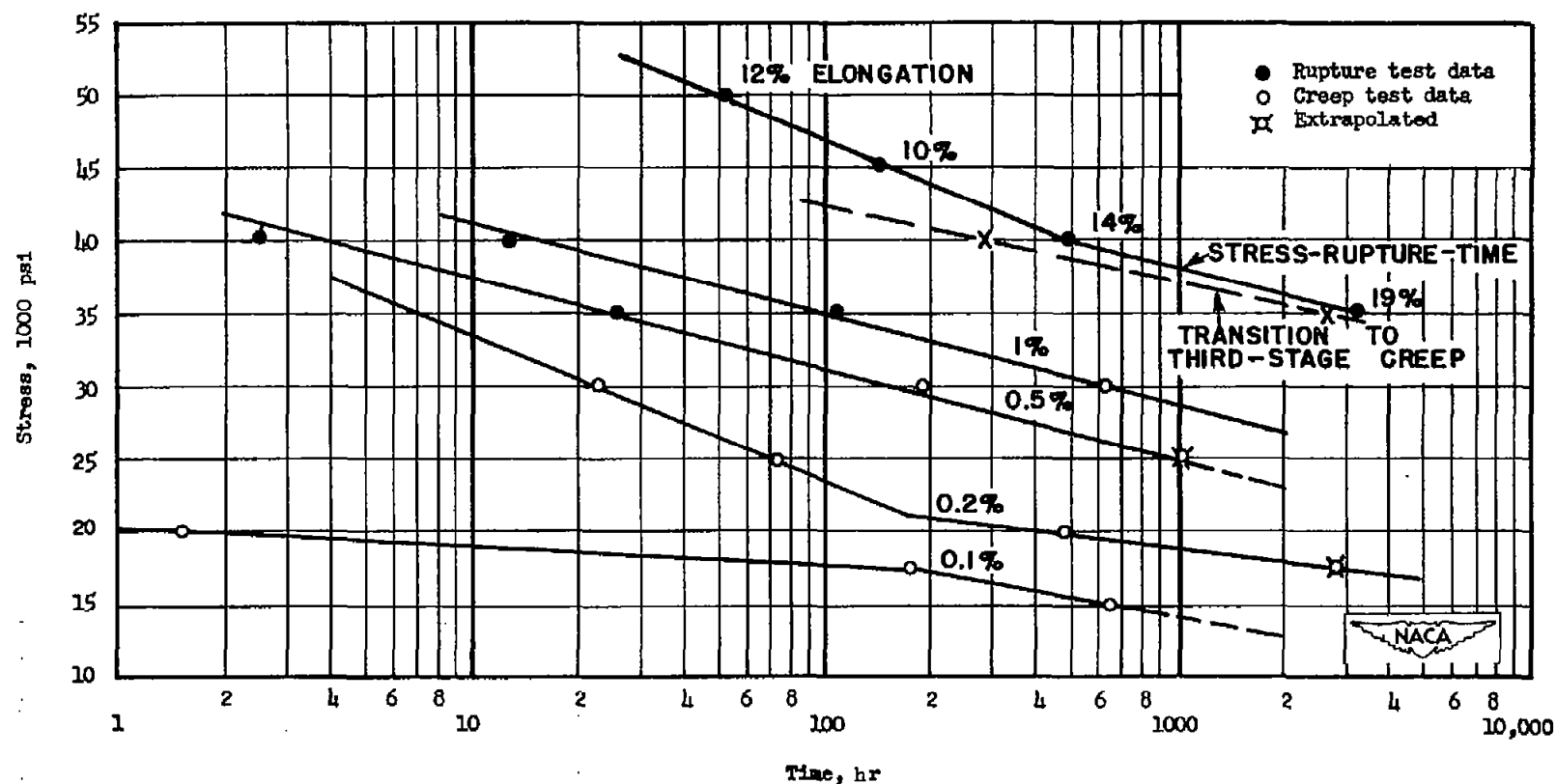


Figure 13.- Curves of stress against time for total deformation at 1200° F for solution-treated and aged low-carbon N-155 alloy bar stock from heat 30276. (Treatment: 2200° F, 1 hr, water-quenched; 1350° F, 50 hr.)

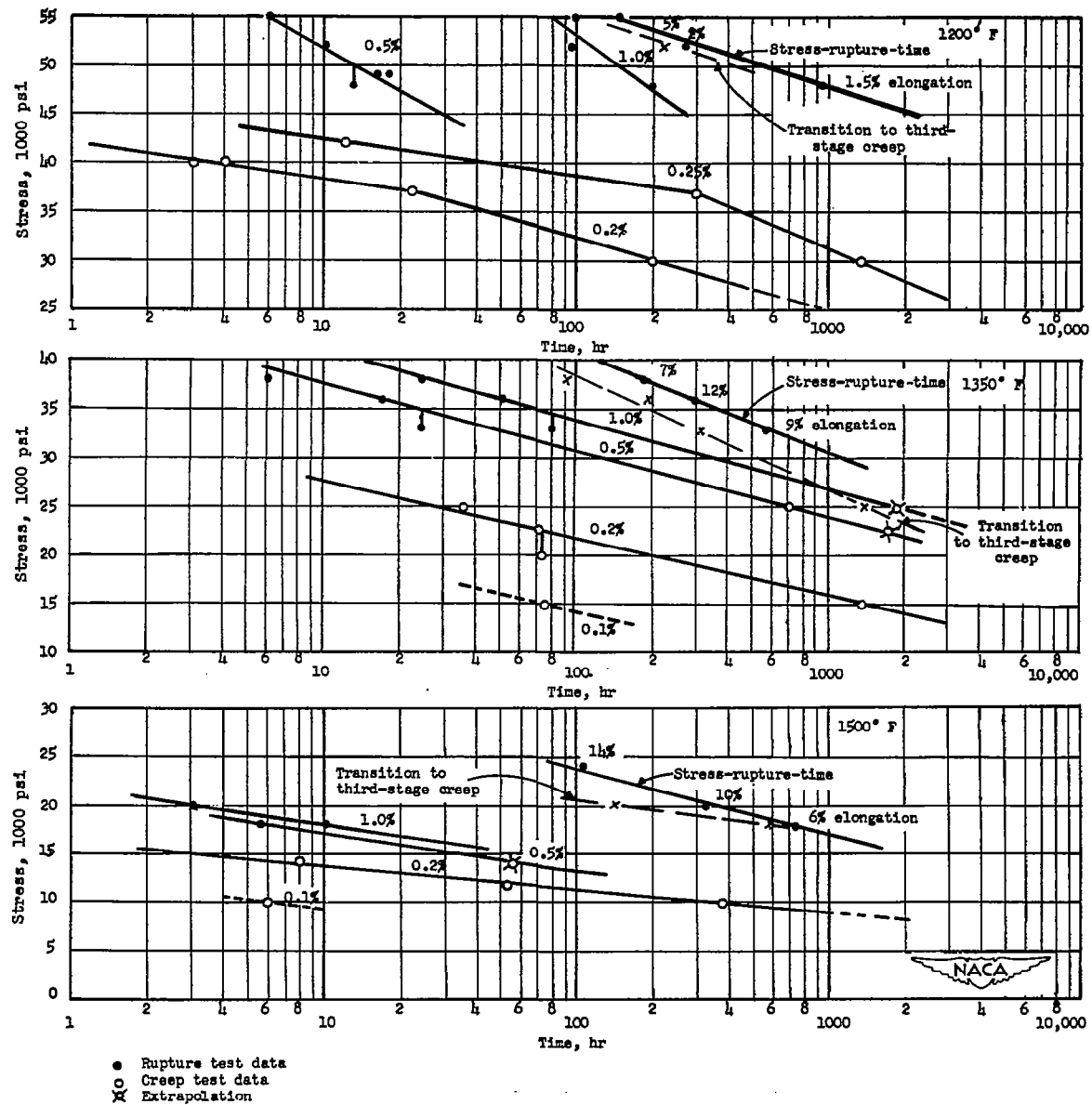


Figure 14.- Curves of stress against time for total deformation at 1200°, 1350°, and 1500° F for solution-treated and hot-cold-worked low-carbon N-155 alloy bar stock from heat A1726. (Treatment: 2050° F, 2 hr, water-quenched; 15-percent hot-cold-work at 1200° F.)

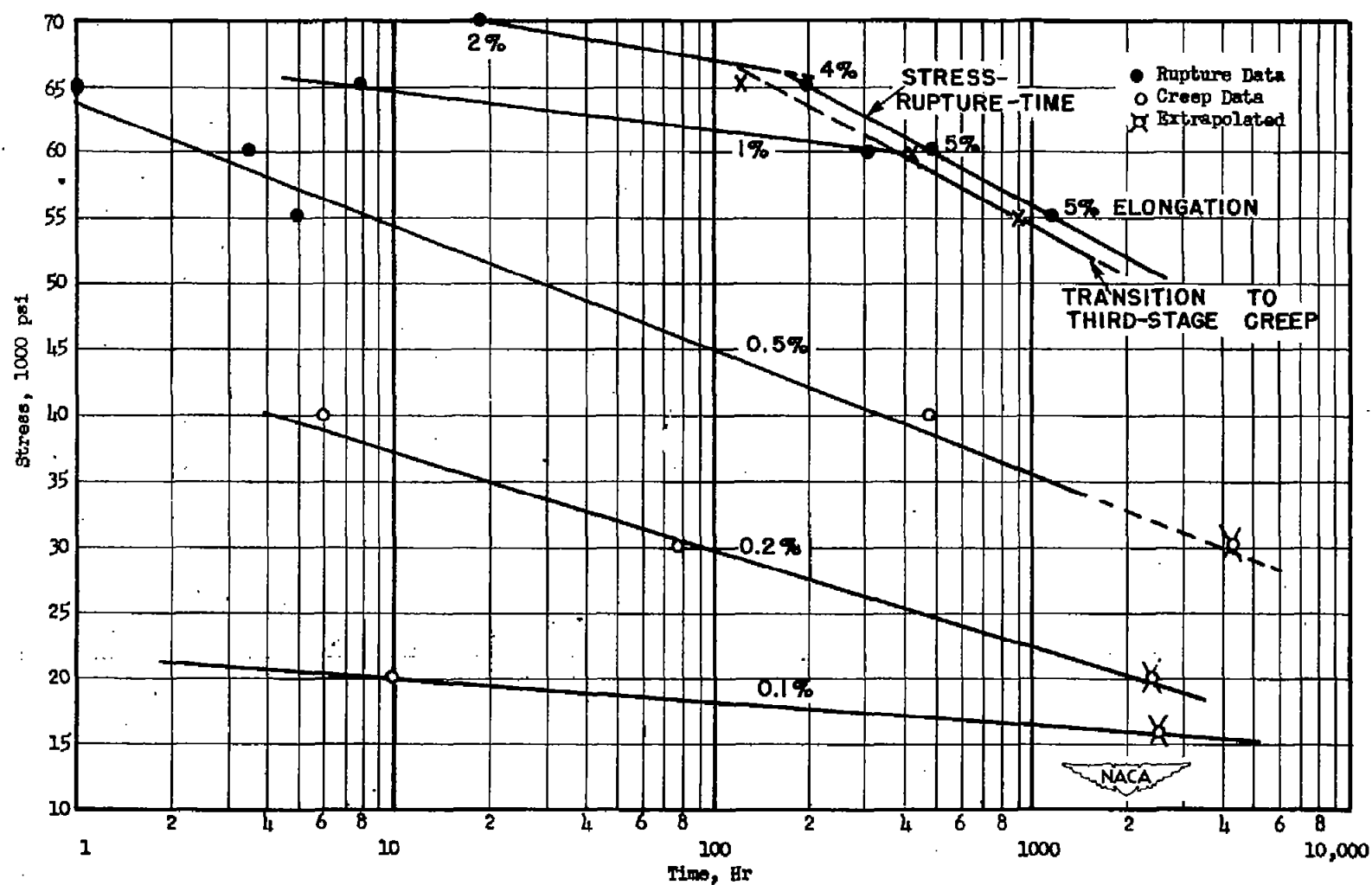


Figure 15.- Curves of stress against time for total deformation at 1200° F for solution-treated and hot-cold-worked low-carbon N-155 alloy bar stock from heat 30276. (Treatment: 2050° F, 2 hr, water-quenched; 25-percent hot-cold-work at 1200° F.)

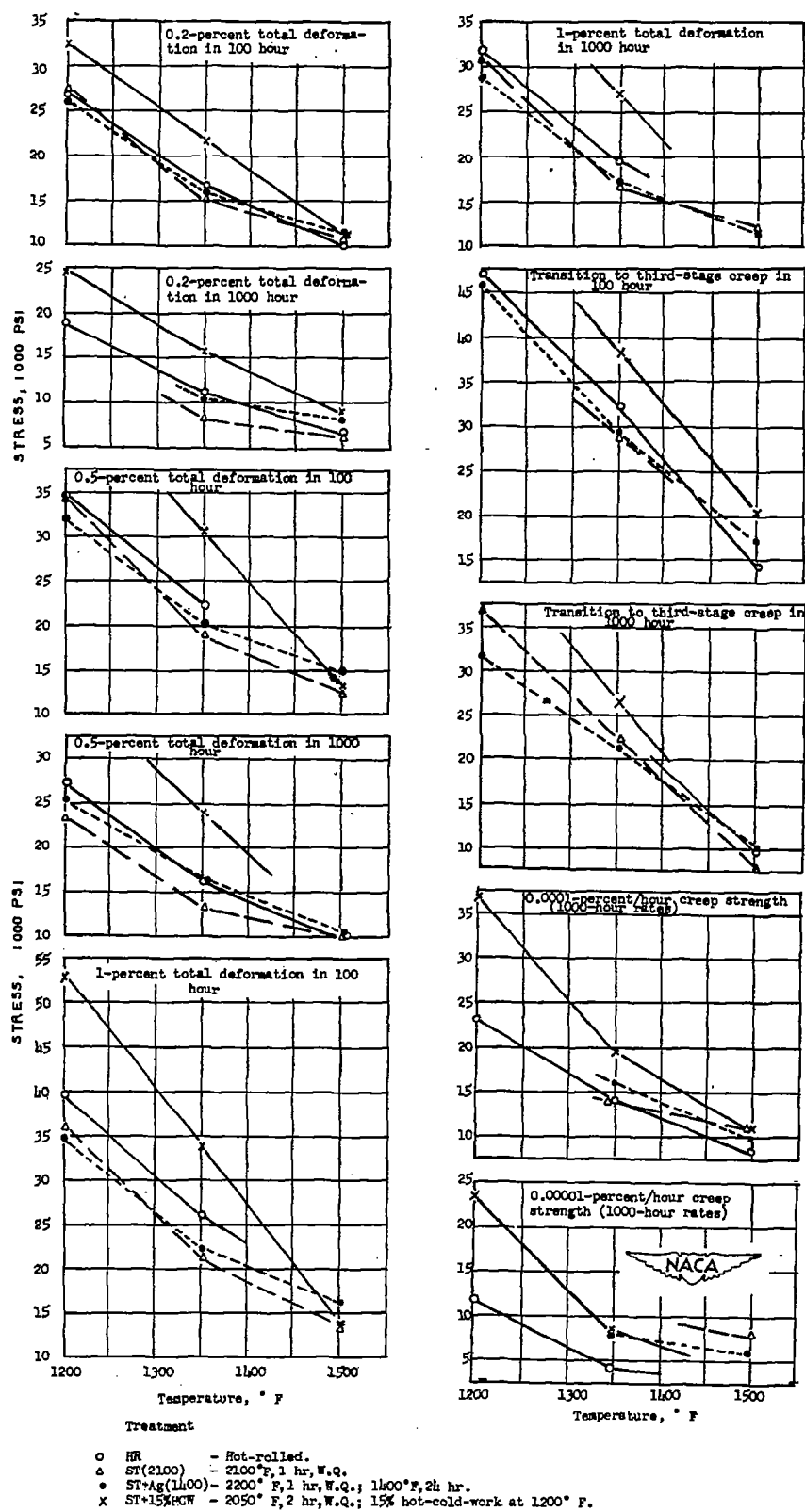


Figure 16.- Influence of testing temperature on total-deformation strengths and creep strengths of low-carbon N-155 alloy bar stock from heat A1726.

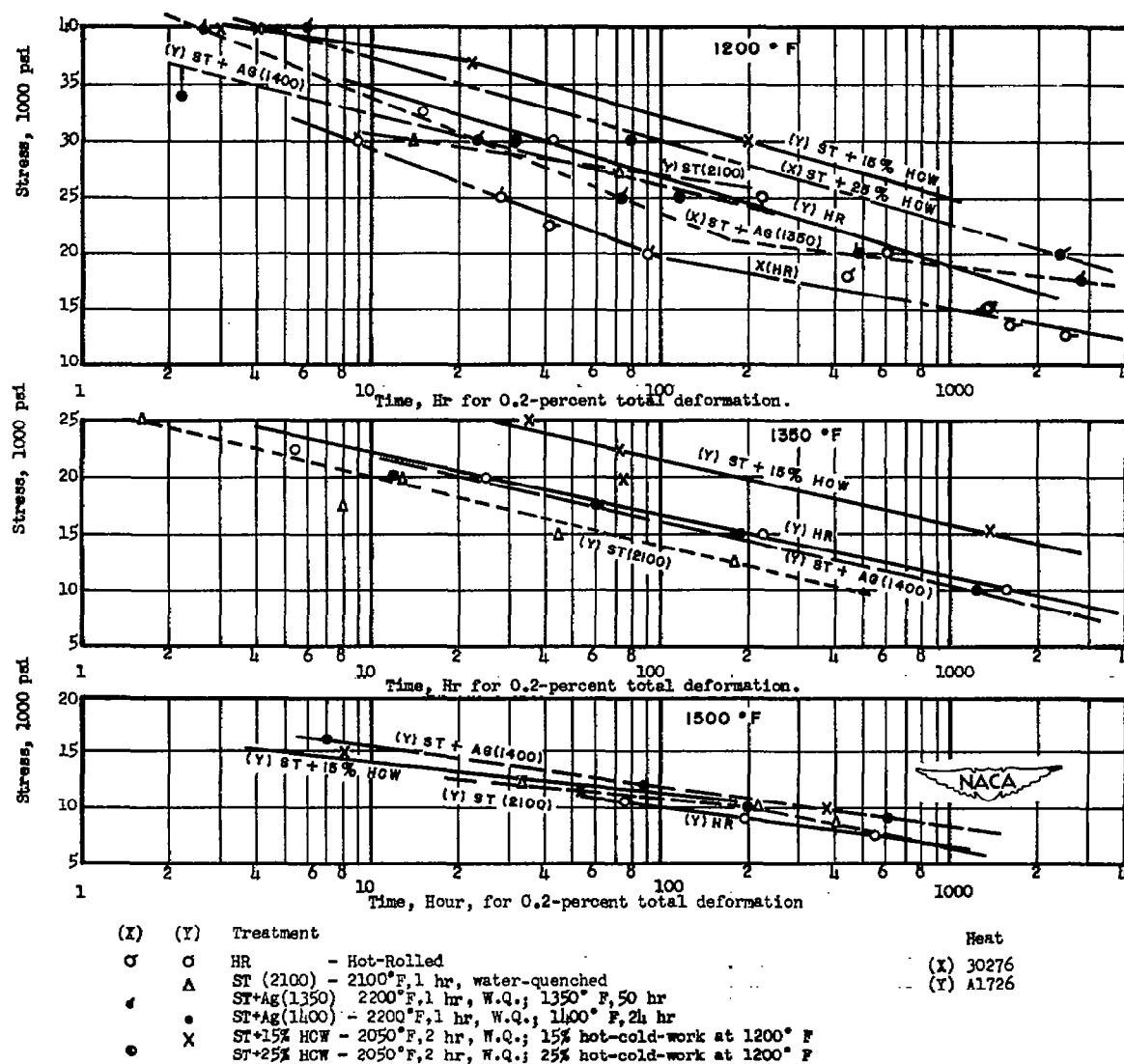


Figure 17.- Comparative 0.2-percent total-deformation characteristics at 1200°, 1350°, and 1500° F for low-carbon N-155 alloy bar stock from two heats.

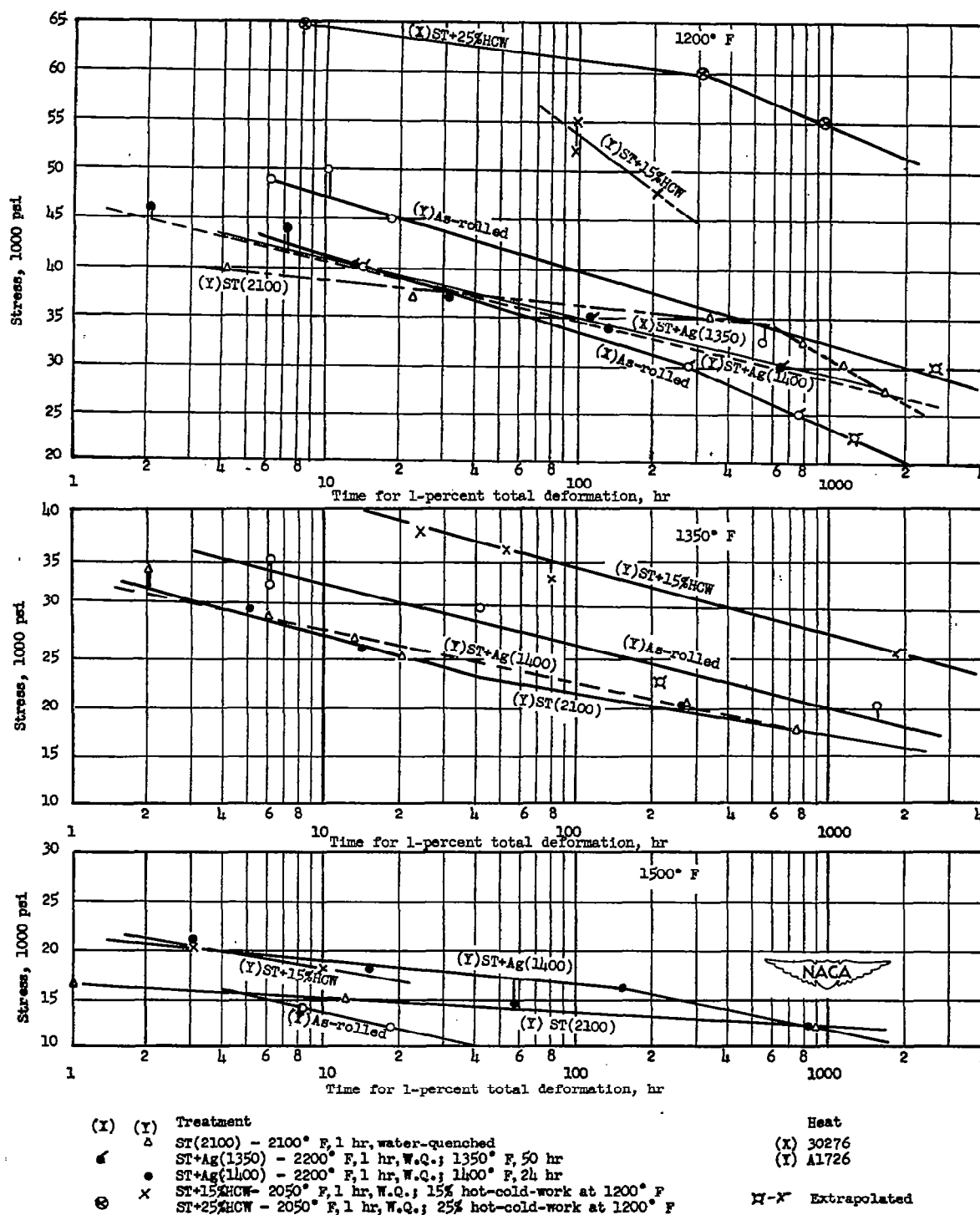


Figure 18.- Comparative 1-percent total-deformation characteristics at 1200°, 1350°, and 1500° F for low-carbon N-155 alloy bar stock from two heats.

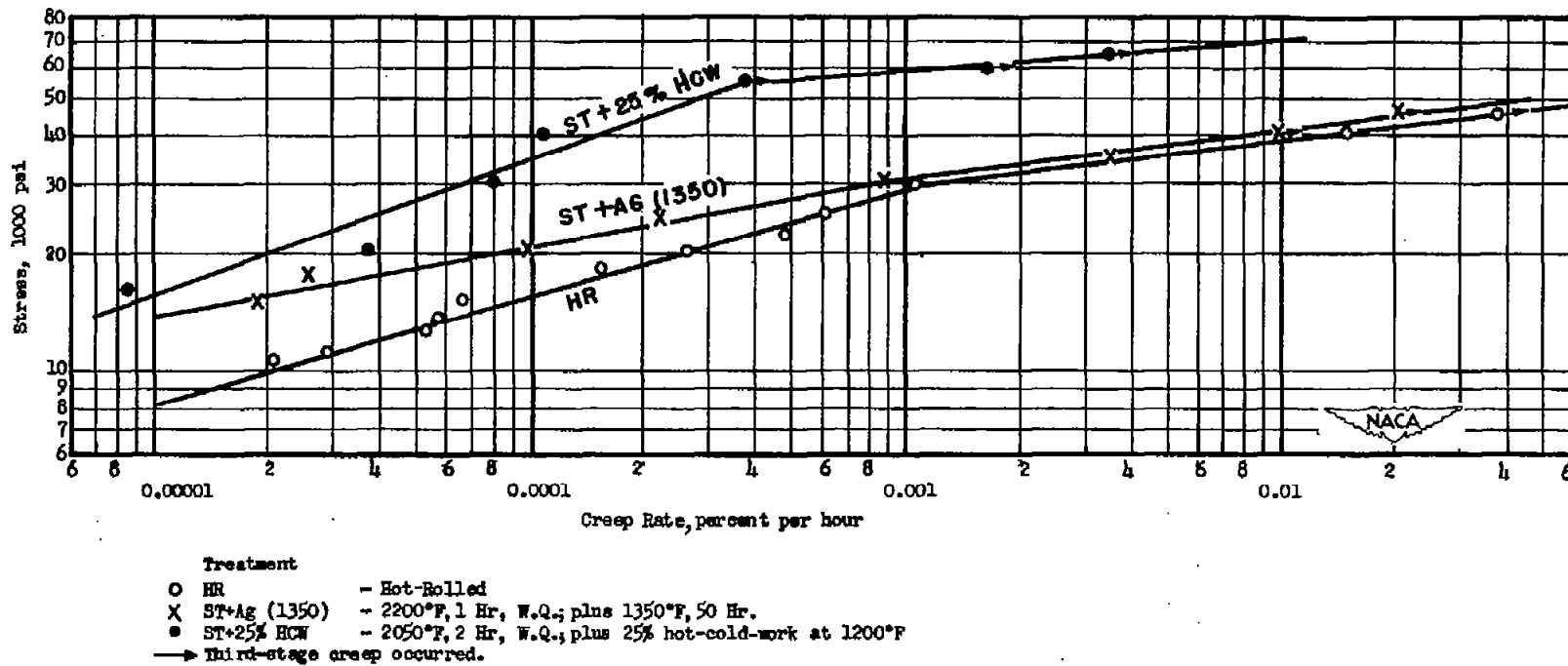
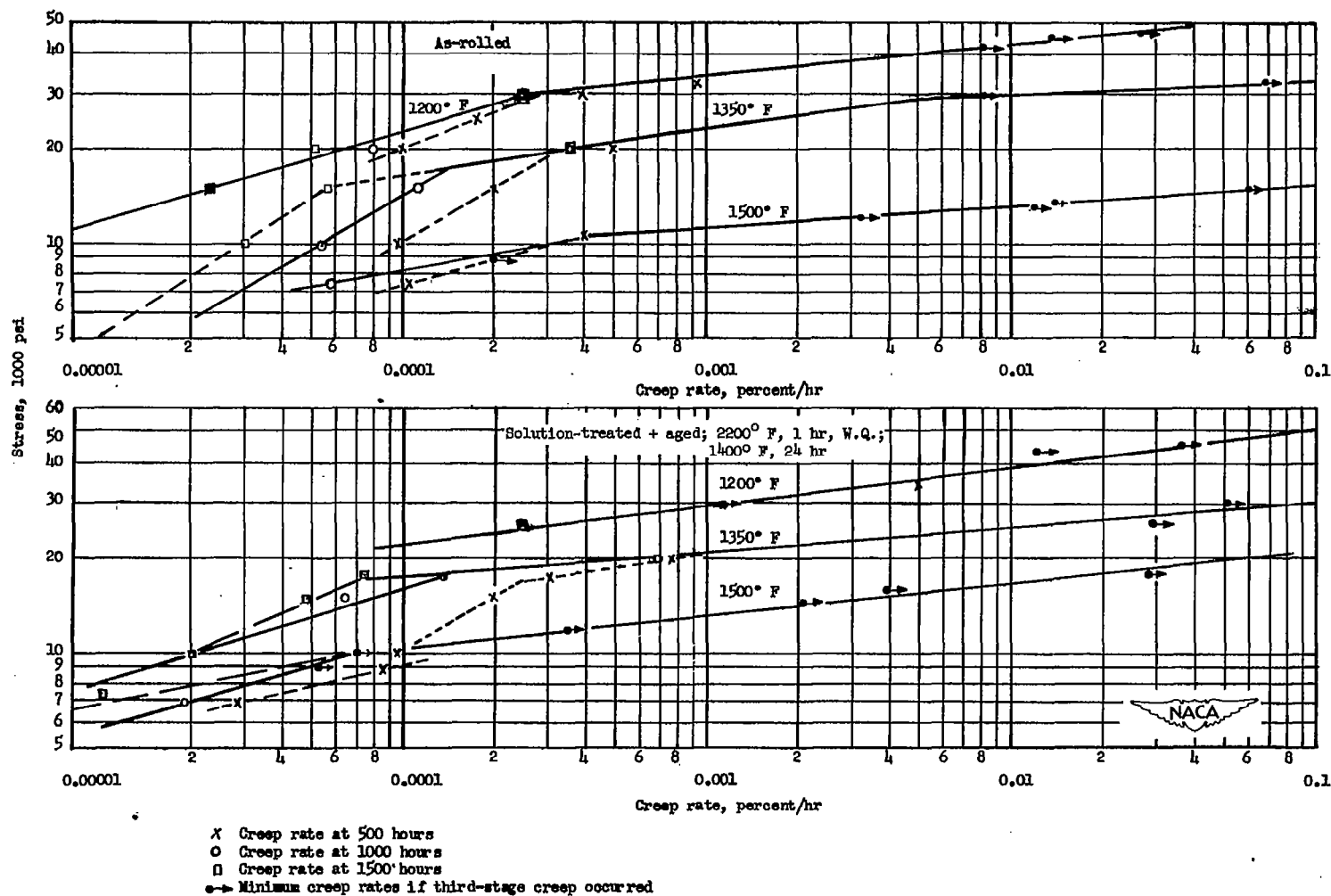
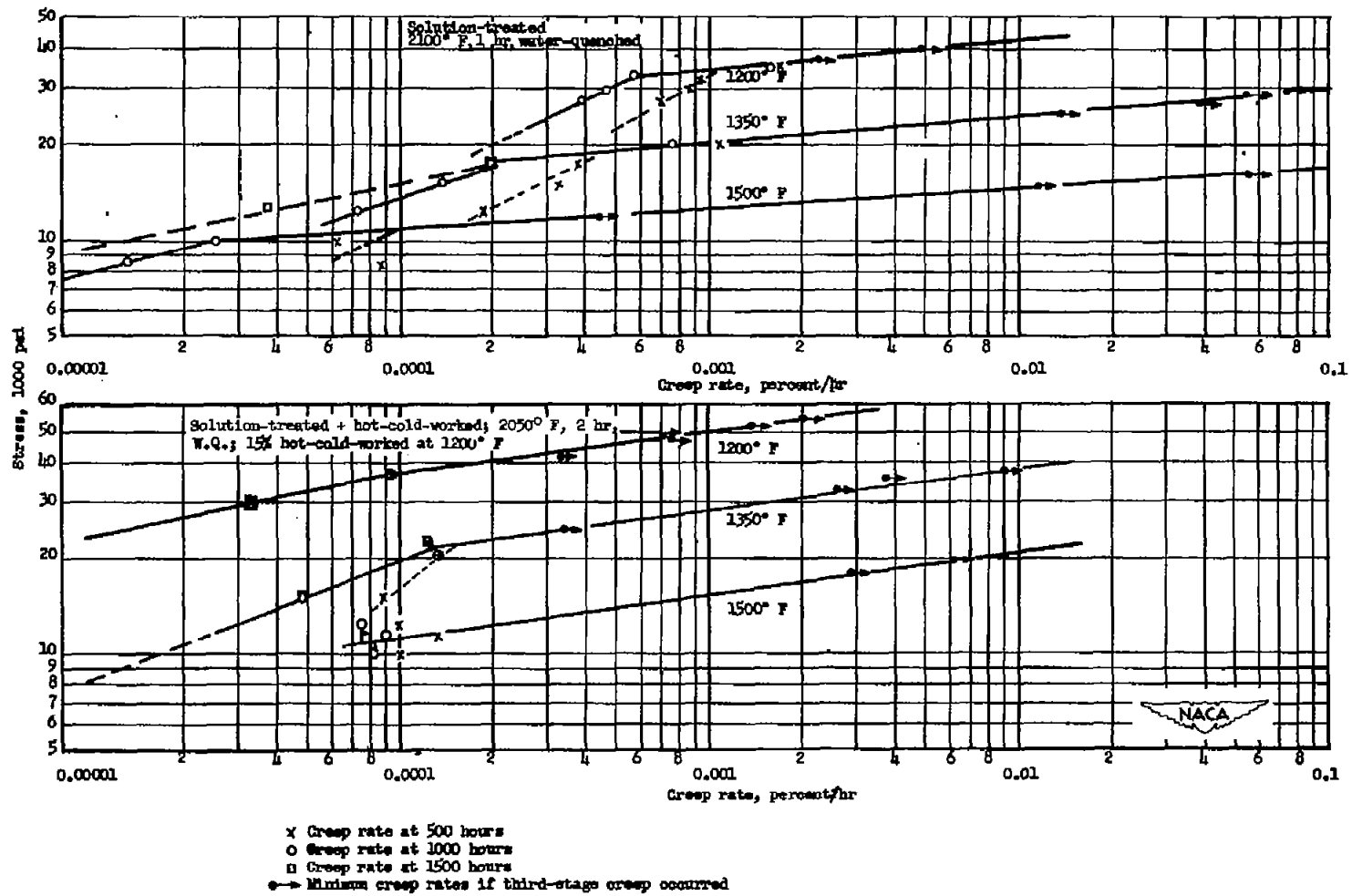


Figure 19.- Curves of stress against creep rate at 1200° F for low-carbon N-155 alloy bar stock from heat 30276. Rates shown are those at 1000 hours or minimum rates if third-stage creep occurred.



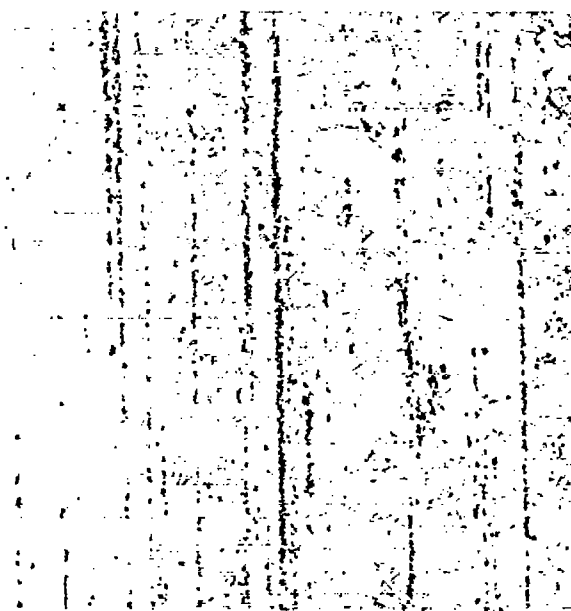
(a) As-rolled and solution-treated plus aged conditions.

Figure 20.- Curves of stress against creep rate at 1200°, 1350°, and 1500° F for low-carbon N-155 alloy bar stock from heat A1726.

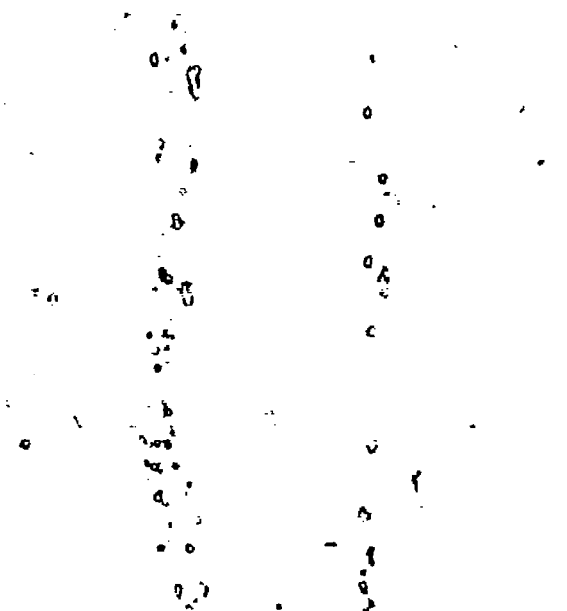


(b) Solution-treated and solution-treated plus hot-cold-worked conditions.

Figure 20.- Concluded.



X100

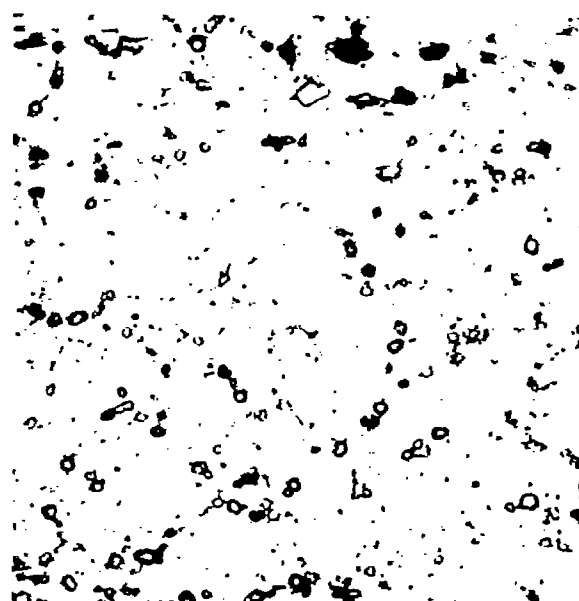


X1000

(a) Heat Al726 - as-rolled.



X100



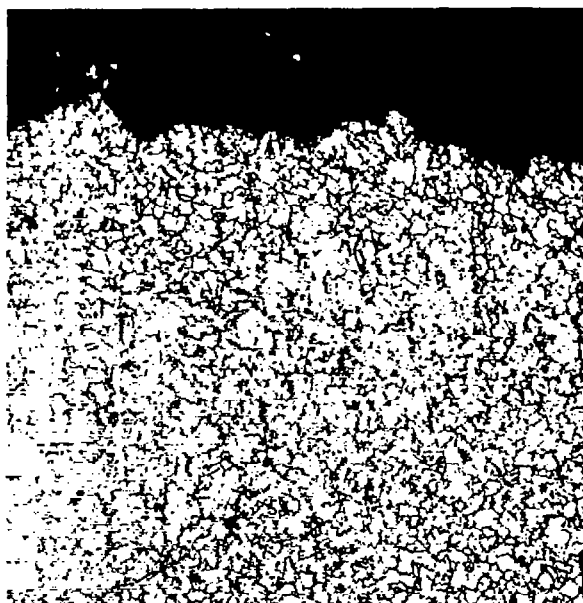
X1000

(b) Heat 30276 - as-rolled.

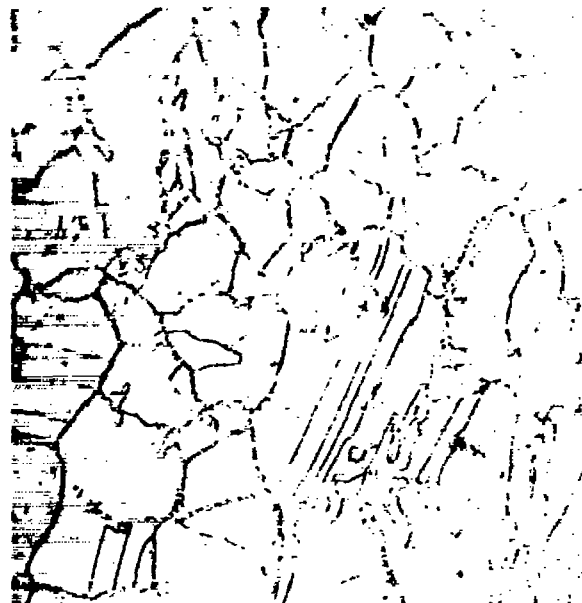


Figure 21.- Original microstructures and microstructures after rupture testing of as-rolled low-carbon N-155 alloy bar stock from heats Al726 and 30276. Electrolytically etched in 10 percent chromic acid.



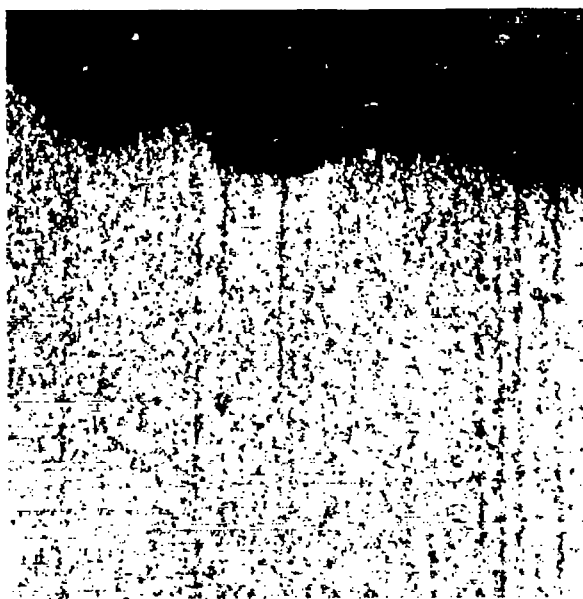


Fracture X100

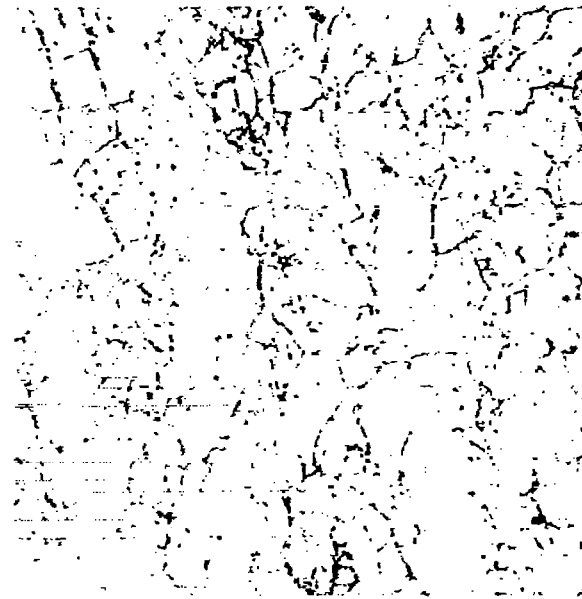


Interior X1000

(c) Heat A1726 - ruptured in 472 hours under 45,000 psi at 1200° F.



Fracture X100



Interior X1000

(d) Heat 30276 - ruptured in 610 hours under 40,000 psi at 1200° F.

Figure 21.- Continued.



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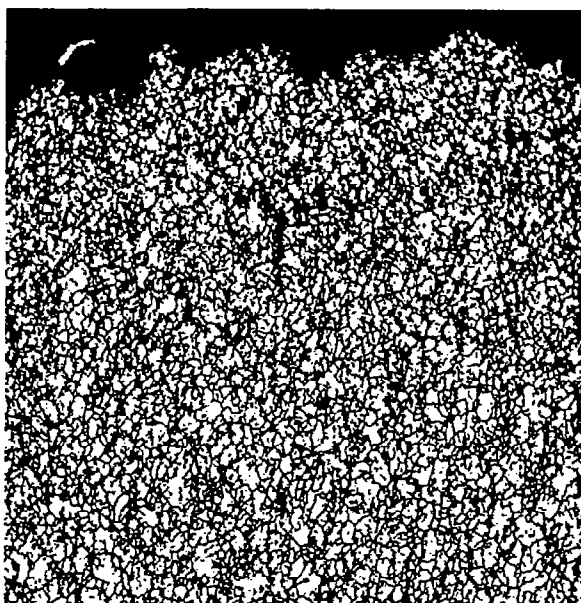
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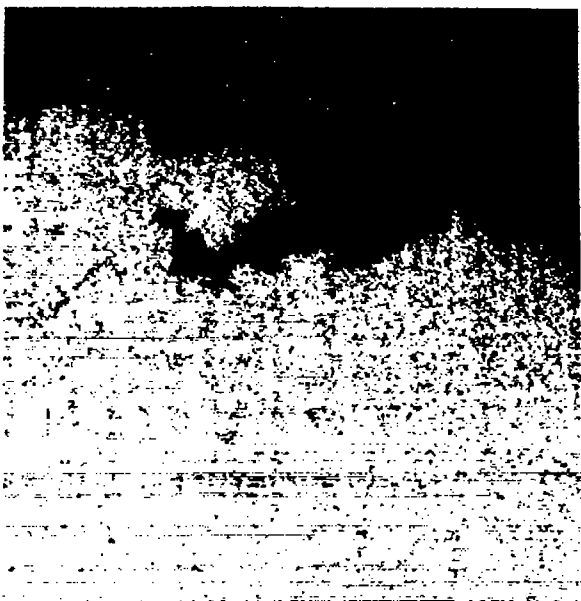


Fracture X100

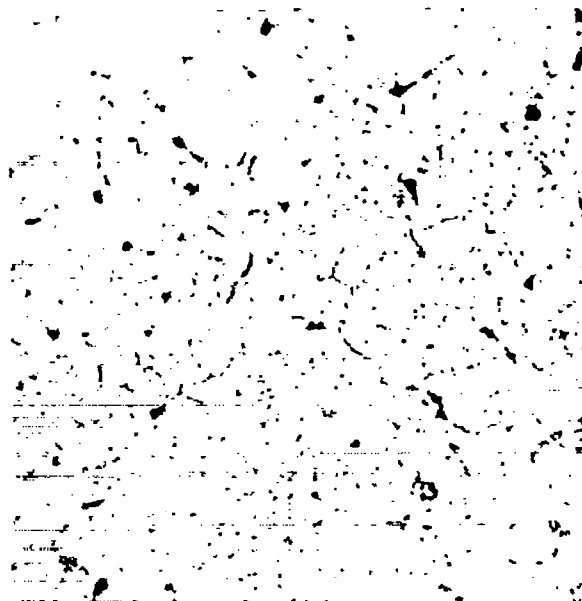


Interior X1000

(e) Heat Al726 - ruptured in 623 hours under 30,000 psi at 1350° F.



Fracture X100



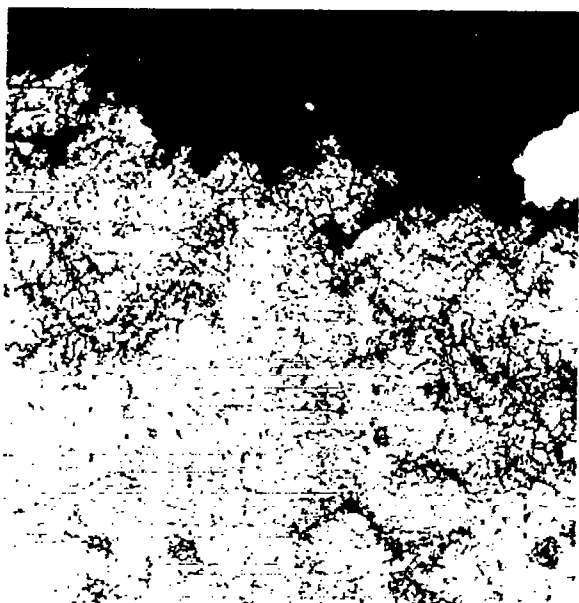
Interior X1000

(f) Heat 30276 - ruptured in 130 hours under 30,000 psi at 1350° F.

Figure 21.- Continued.





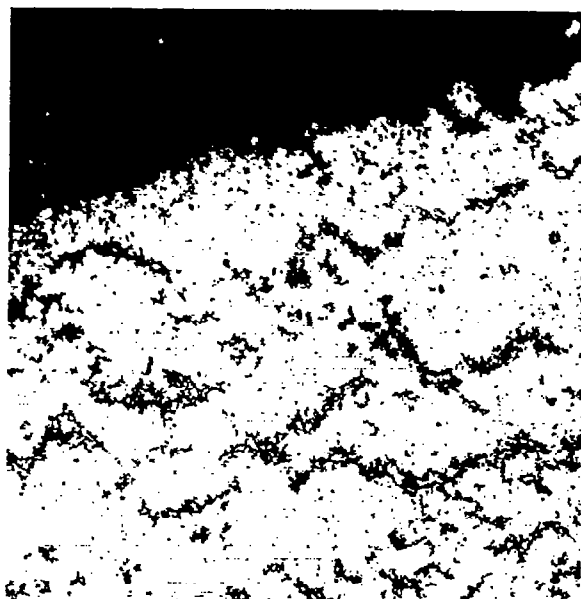


Fracture X100

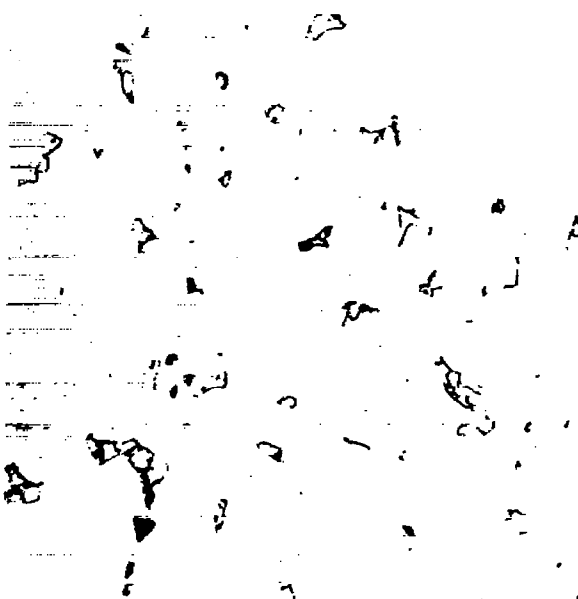


Interior X1000

(g) Heat A1726 - ruptured in 747 hours under 12,000 psi at 1500° F.



Fracture X100



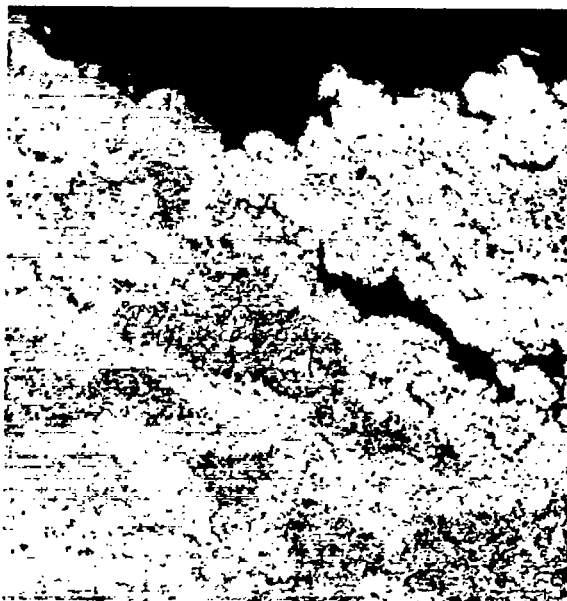
Interior X1000

(h) Heat 30276 - ruptured in 430 hours under 9000 psi at 1500° F.

Figure 21.- Continued.





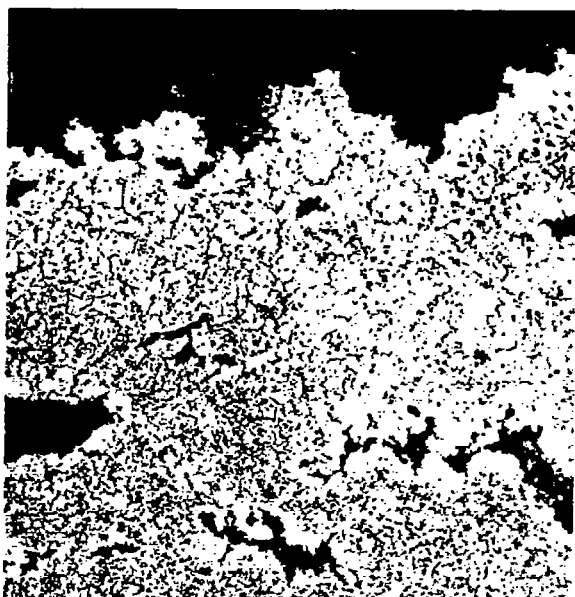


Fracture X100

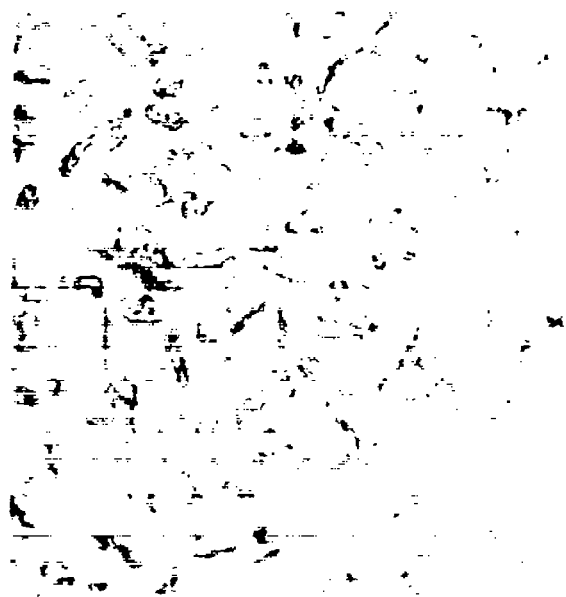


Interior X1000

(i) Heat A1726 - ruptured in 1051 hours under 4000 psi at 1650° F.



Fracture X100



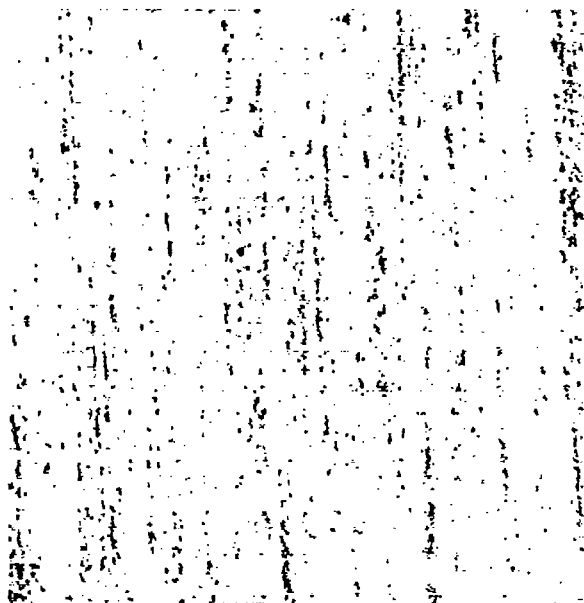
Interior X1000

(j) Heat A1726 - ruptured in 847 hours under 1500 psi at 1800° F.

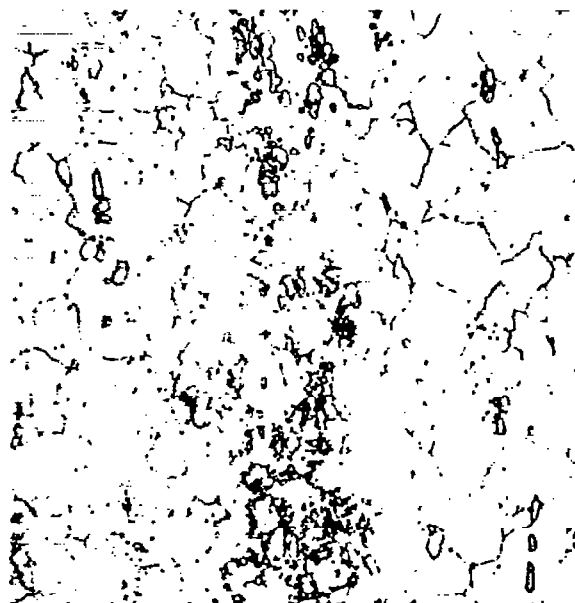
Figure 21.- Concluded.





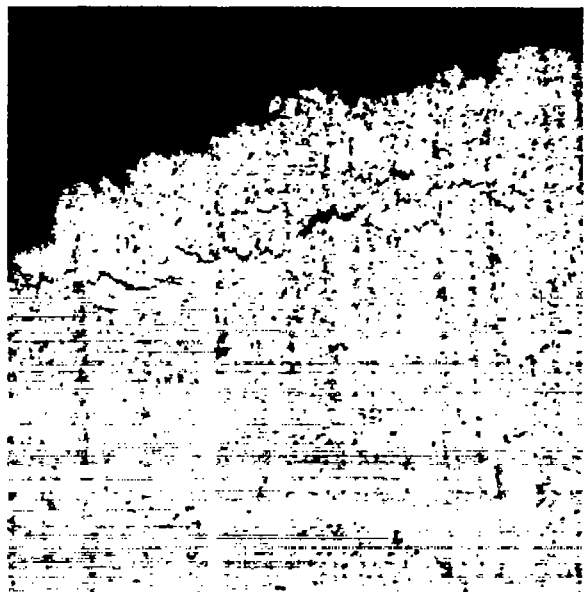


X100



X1000

(a) Initial.



Fracture X100



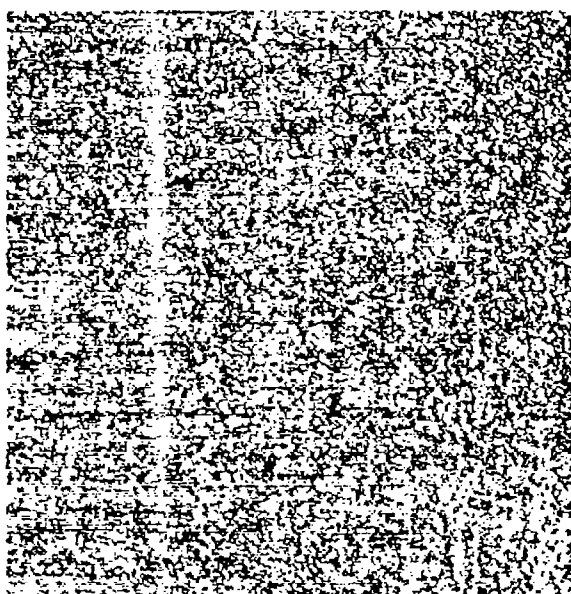
Interior X1000

(b) Ruptured in 499 hours under 22,000 psi at 1350° F.

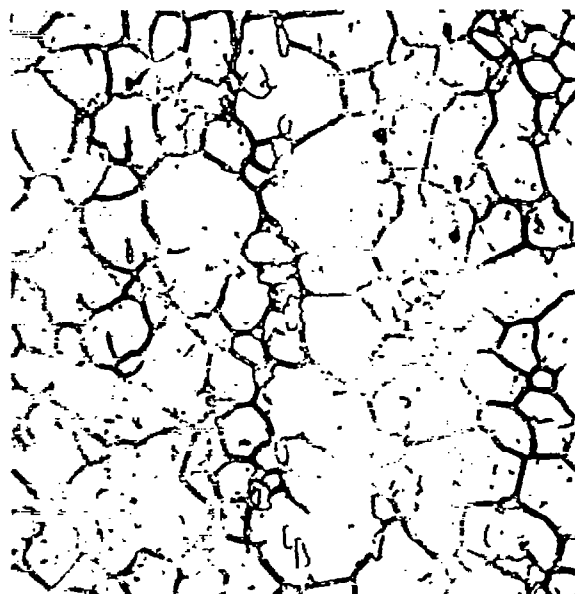


Figure 22.- Initial microstructure and microstructure after rupture testing of as-rolled and hot-cold-worked low-carbon N-155 alloy bar stock from heat 30276. Electrolytically etched in 10 percent chromic acid. (Treatment: As-rolled; 15-percent hot-cold-work at 1200° F.)



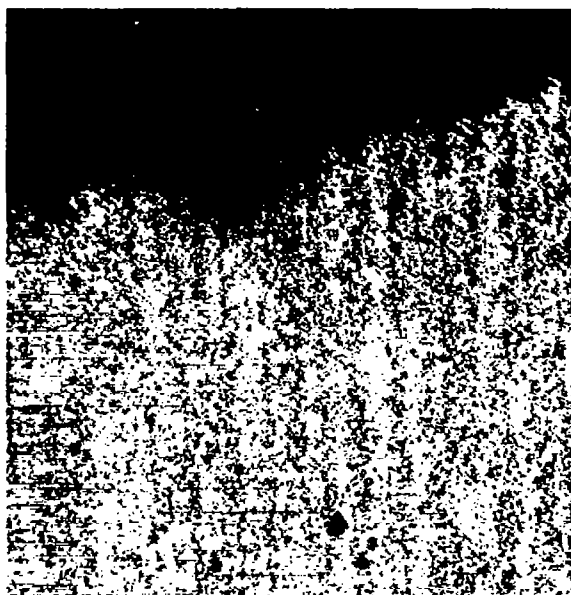


X100

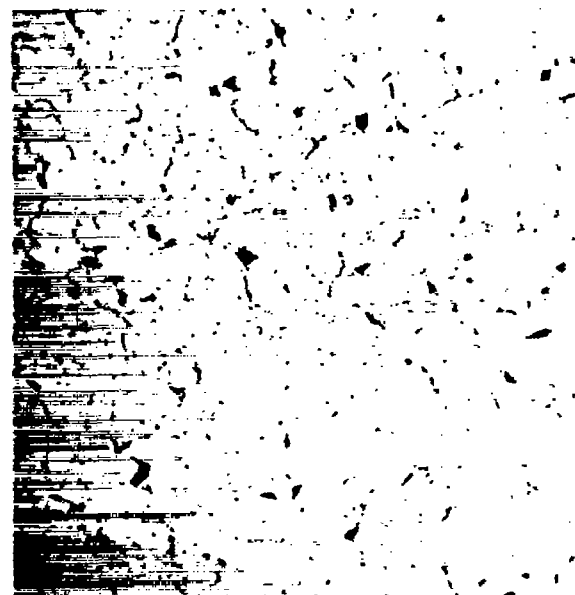


X1000

(a) Initial.



Fracture X100



Interior X1000

(b) Ruptured in 639 hours under 20,000 psi at 1350° F.



Figure 23.- Initial microstructure and microstructure after rupture testing for as-rolled and aged low-carbon N-155 alloy bar stock from heat 30276. Electrolytically etched in 10 percent chromic acid. (Treatment: As-rolled; 1350° F, 24 hr.)

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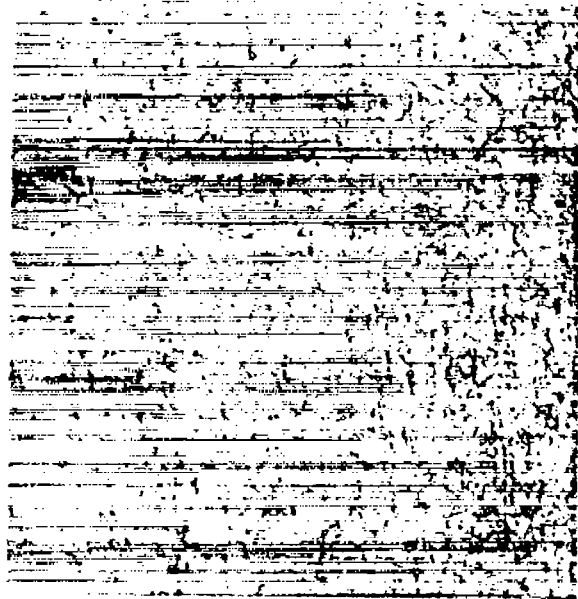
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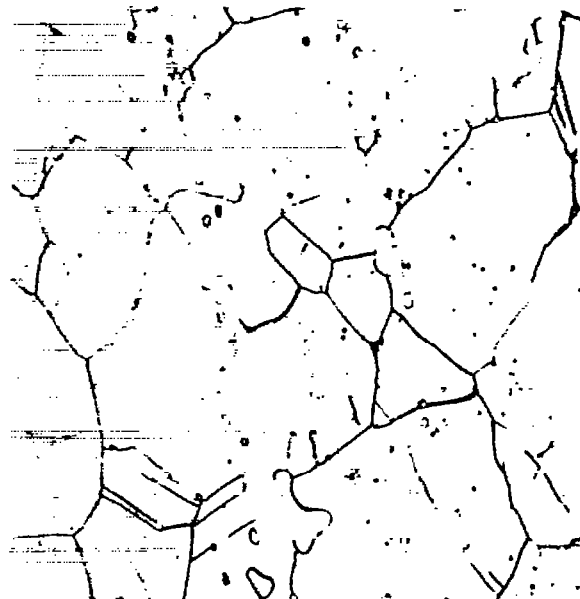
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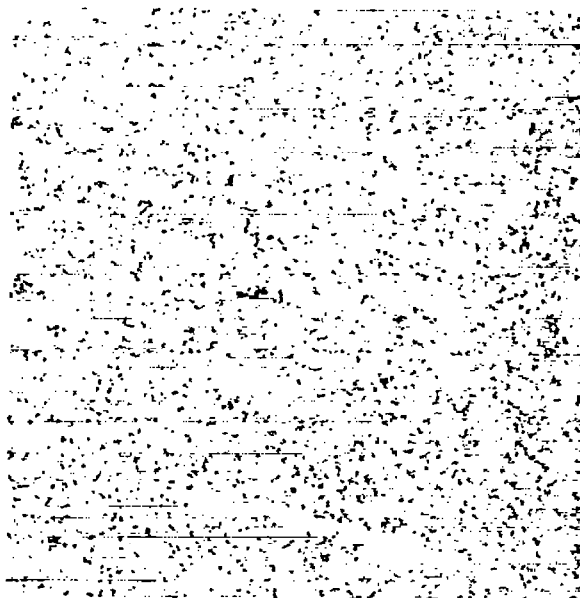


X100

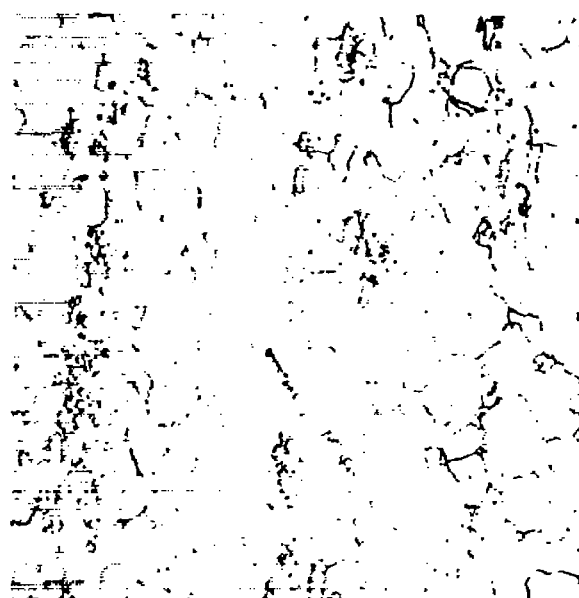


X1000

(a) Heat Al726-initial.



X100



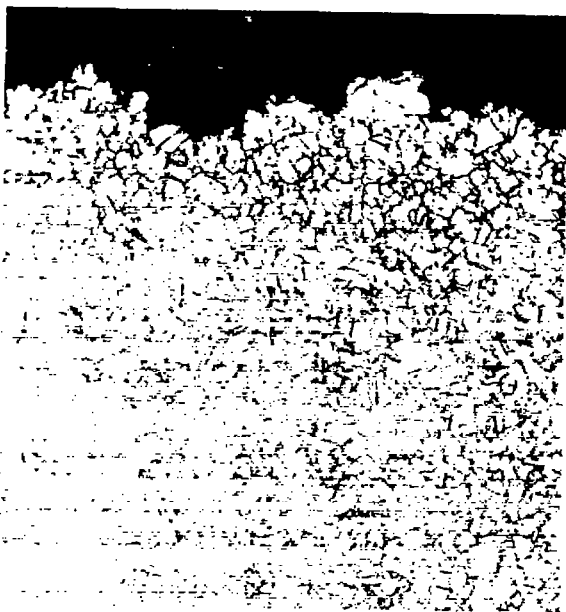
X1000

(b) Heat 30276-initial.

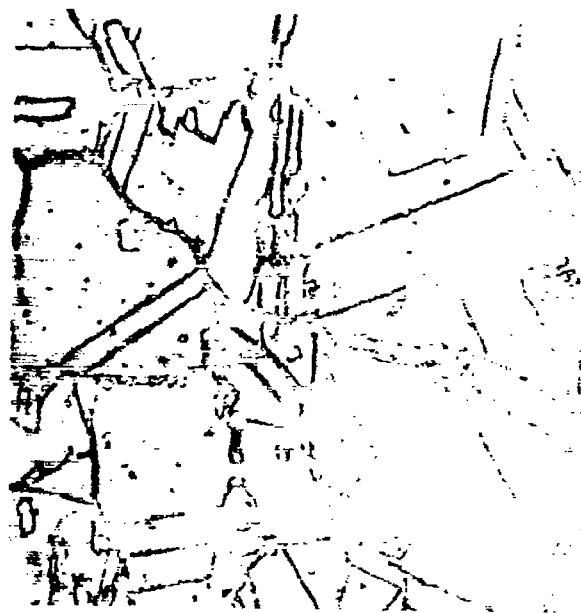


Figure 24.- Initial microstructures and microstructures after rupture testing of solution-treated and hot-cold-worked low-carbon N-155 alloy bar stock from heats Al726 and 30276. Electrolytically etched in 10 percent chromic acid. (Treatment: 2050° F, 2 hr, water-quenched; 15-percent hot-cold-work at 1200° F.)



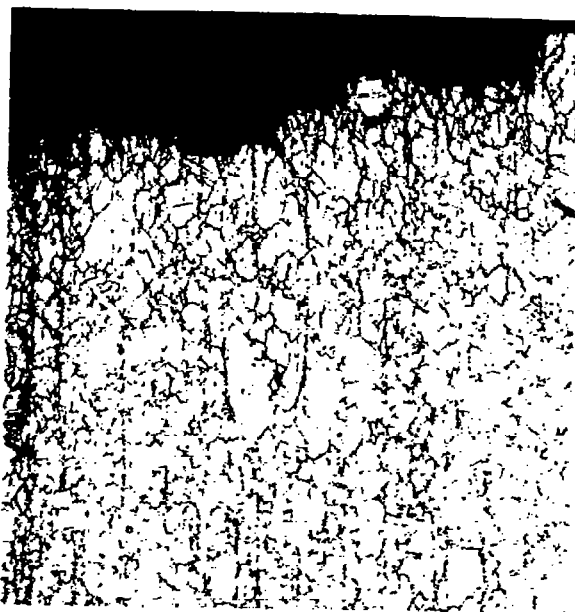


Fracture X100

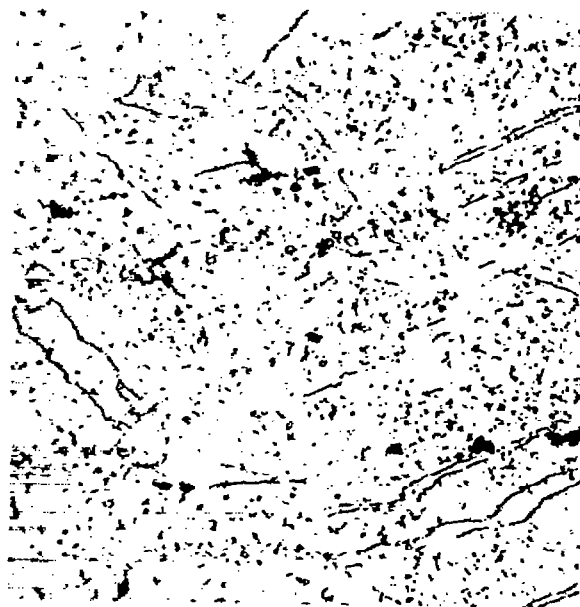


Interior X1000

(c) Heat A1726 - ruptured in 942 hours under 48,000 psi at 1200° F.



Fracture X100



Interior X1000

(d) Heat 30276 - ruptured in 1556 hours under 52,000 psi at 1200° F.

Figure 24.- Continued.



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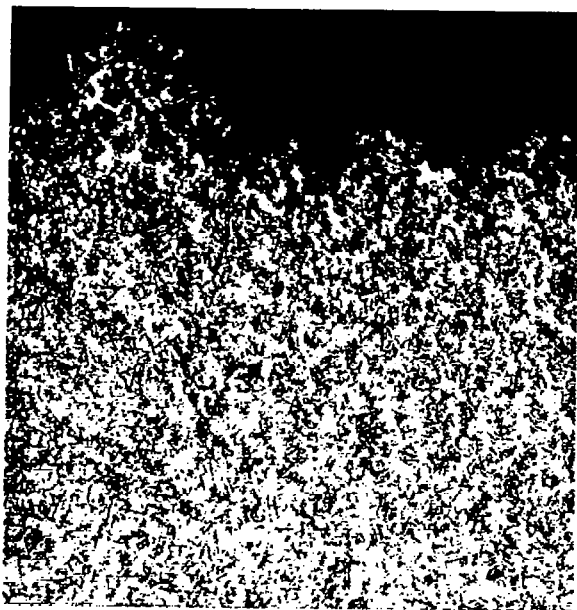
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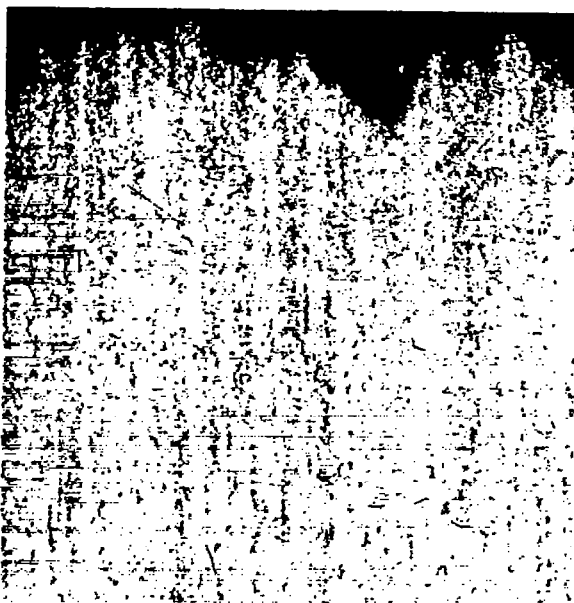


Fracture X100

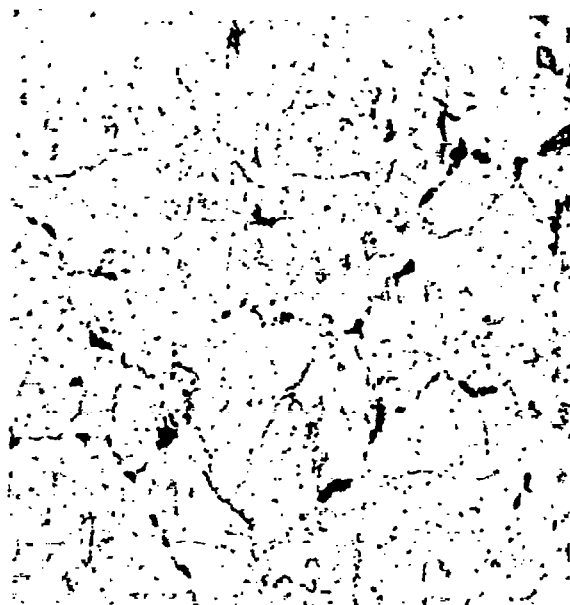


Interior X1000

(e) Heat A1726 - ruptured in 564 hours under 33,000 psi at 1350° F.



Fracture X100



Interior X1000

(f) Heat 30276 - ruptured in 593 hours under 30,000 psi at 1350° F.

Figure 24.- Continued.





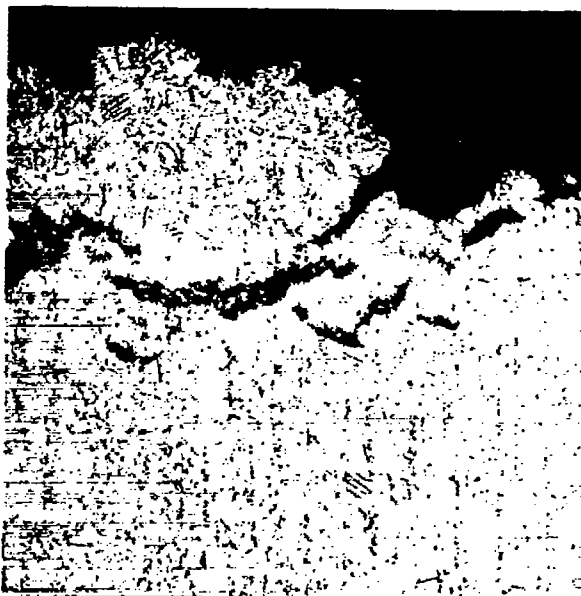


Fracture X100



Interior X1000

(g) Heat Al726 - ruptured in 739 hours under 18,000 psi at 1500° F.



Fracture X100



Interior X1000

(h) Heat 30276 - ruptured in 421 hours under 13,000 psi at 1500° F.

Figure 24.- Continued.



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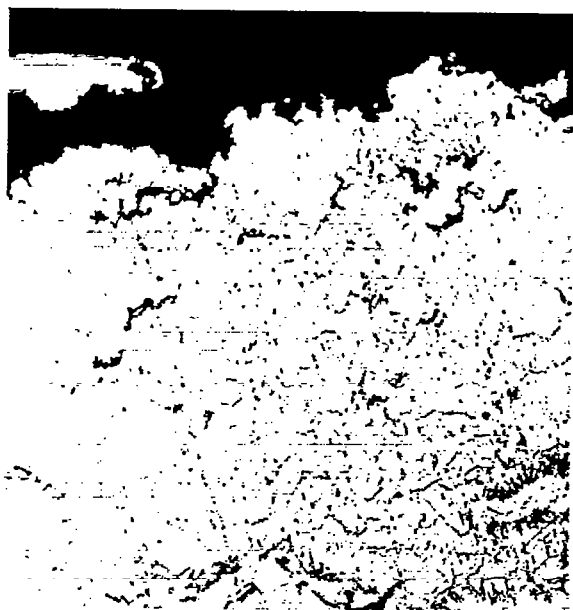
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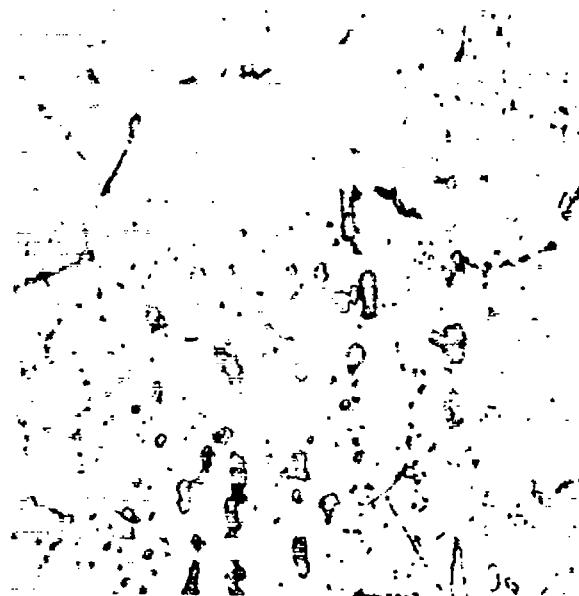
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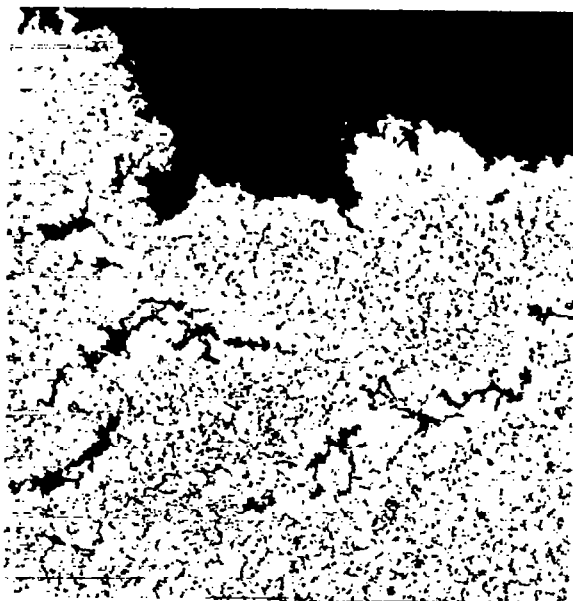


Fracture X100

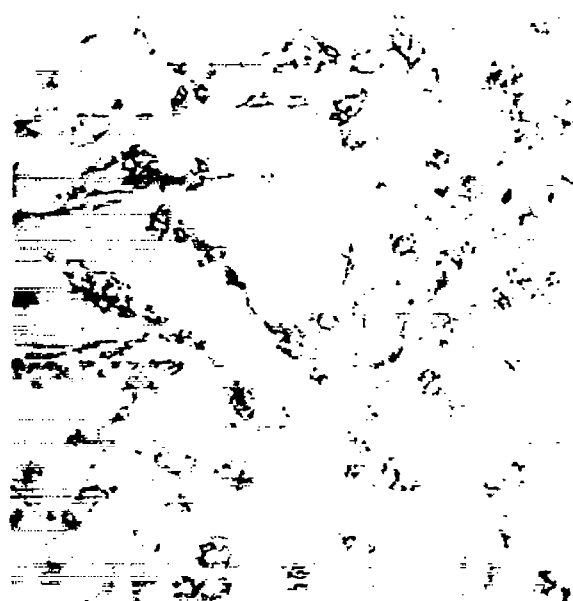


Interior X1000

(i) Heat A1726 - ruptured in 676 hours under 7000 psi at 1650° F.



Fracture X100



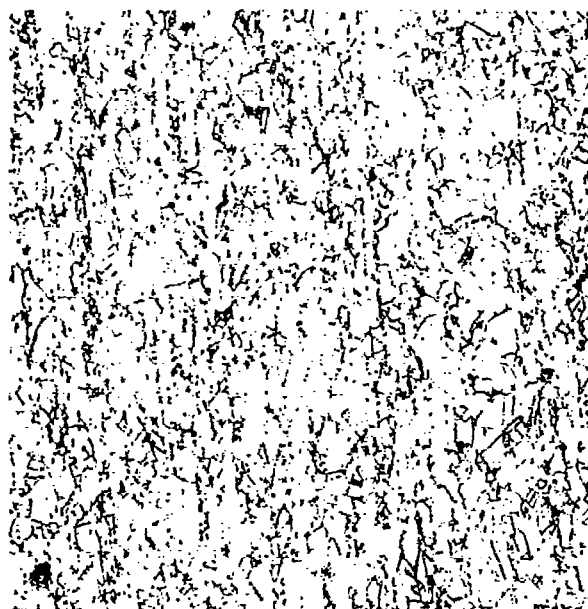
Interior X1000

(j) Heat A1726 - ruptured in 1004 hours under 1850 psi at 1800° F.

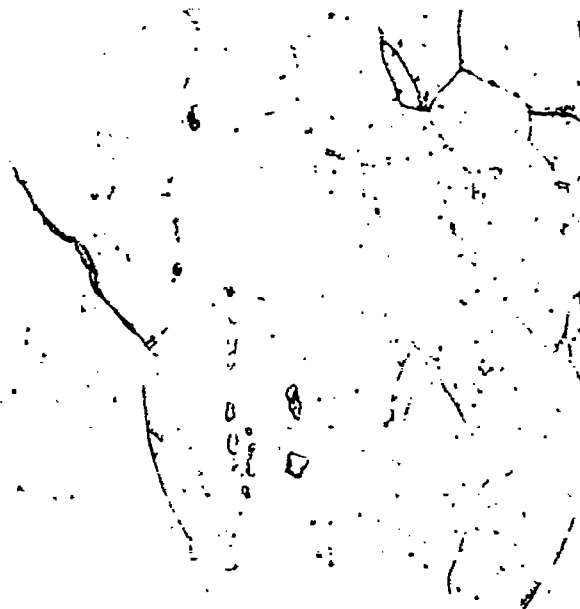
Figure 24.- Concluded.







X100



X1000

(a) Initial.



Fracture X100



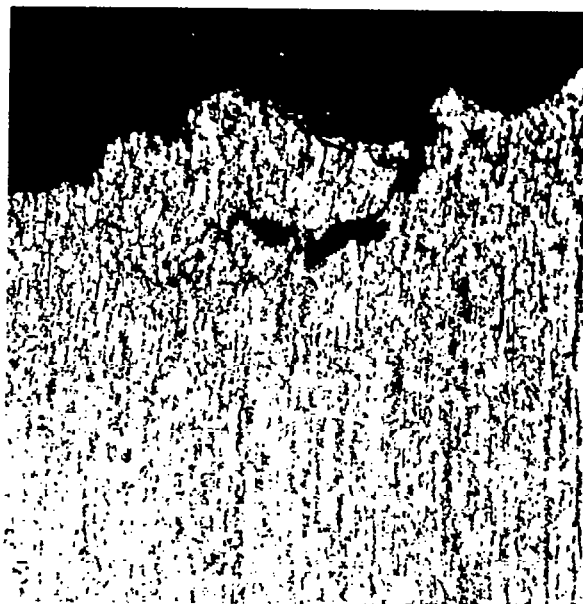
Interior X1000

(b) Ruptured in 1142 hours under 55,000 psi at 1200° F.



Figure 25.- Initial microstructure and microstructures after rupture testing of low-carbon N-155 alloy bar stock from heat 30276 hot-cold-worked 25 percent. Electrolytically etched in 10 percent chromic acid. (Treatment: 2050° F, 2 hr, water-quenched; 25-percent hot-cold-work at 1200° F.)





Fracture X100



Interior X1000

(c) Ruptured in 446 hours under 30,000 psi at 1350° F.



Fracture X100



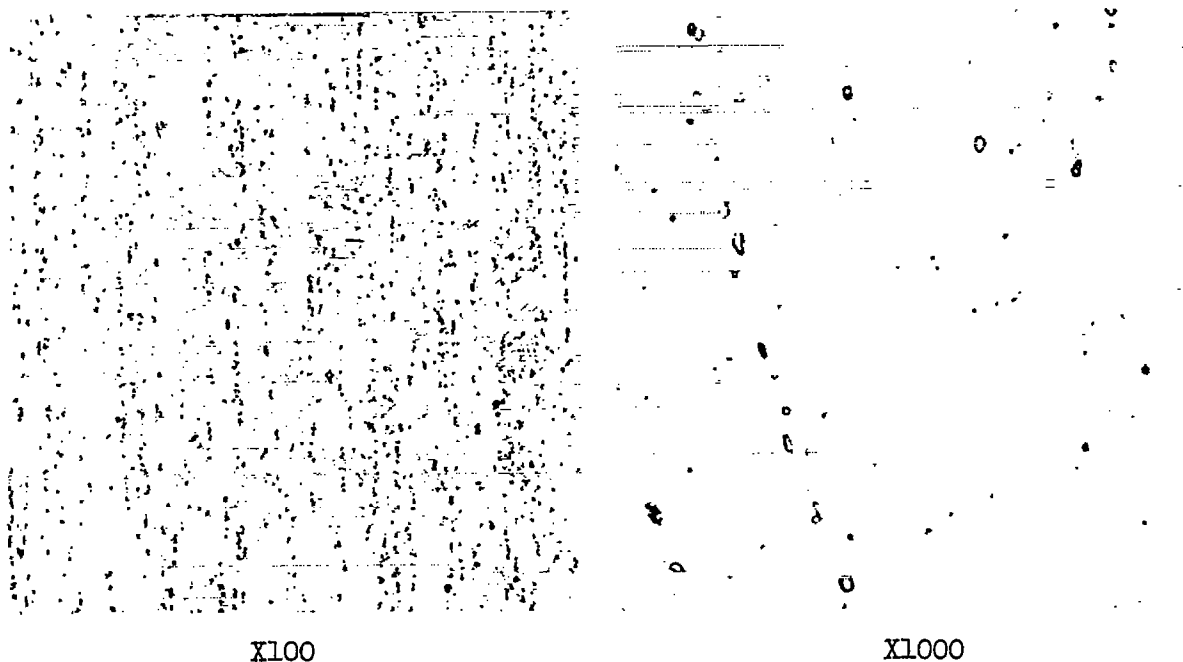
Interior X1000

(d) Ruptured in 340 hours under 13,000 psi at 1500° F.

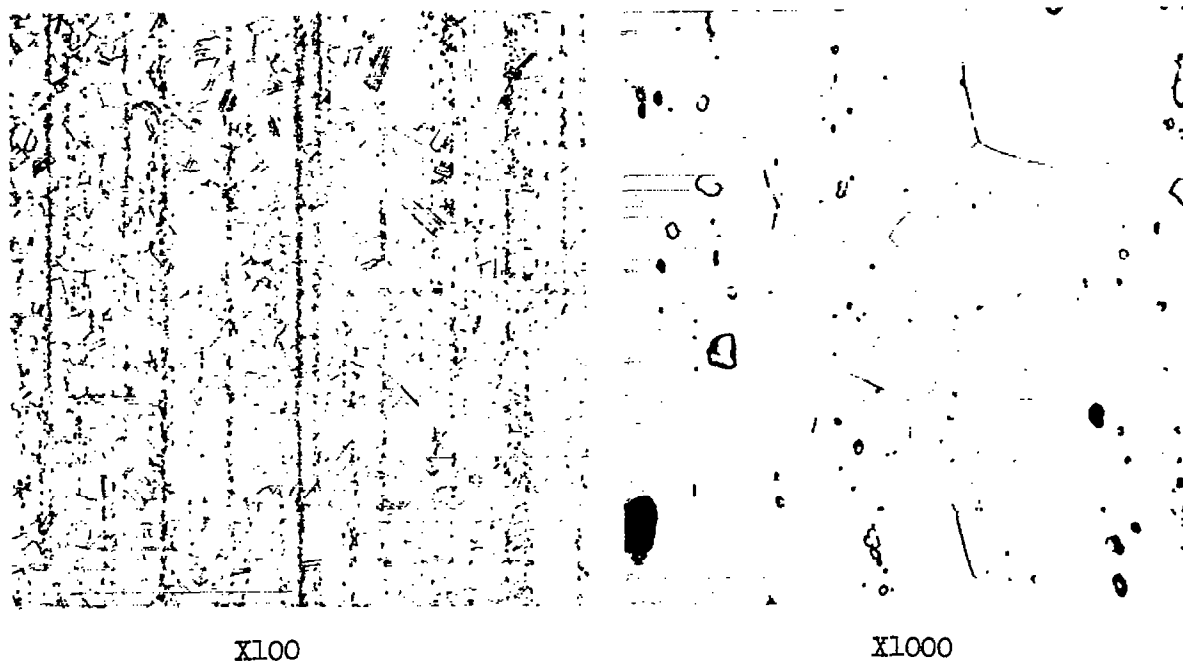
Figure 25.- Concluded.







(a) Heat Al726 - initial.

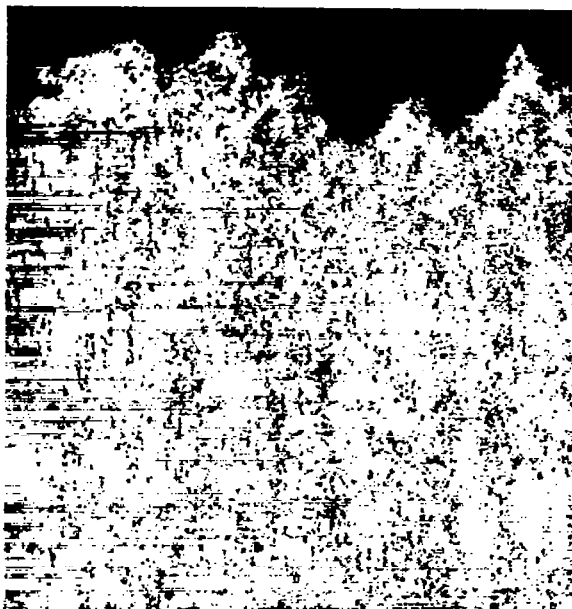


(b) Heat 30276 - initial.



Figure 26.- Initial microstructures and microstructures after rupture testing of solution-treated low-carbon N-155 alloy bar stock from heats Al726 and 30276. Electrolytically etched in 10 percent chromic acid. (Treatment: 2100° F, 1 hr, water-quenched.)



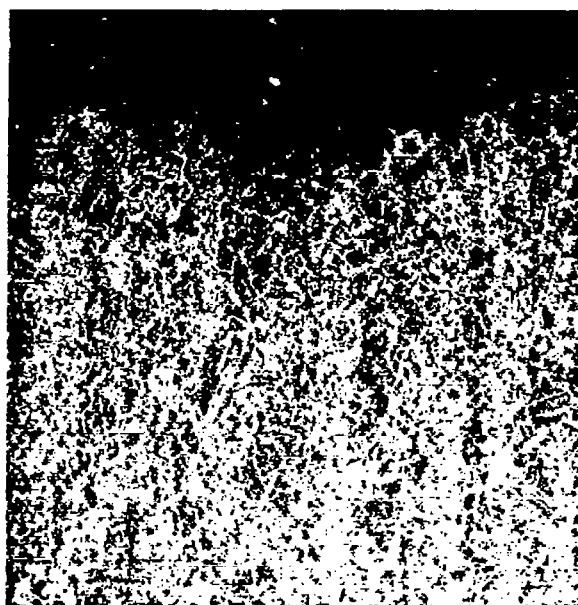


Fracture X100

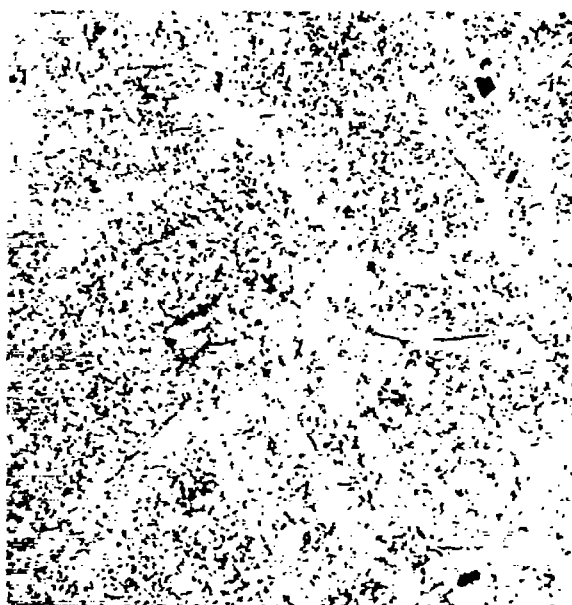


Interior X1000

(c) Heat Al726 - ruptured in 696 hours under 25,000 psi at 1350° F.



Fracture X100



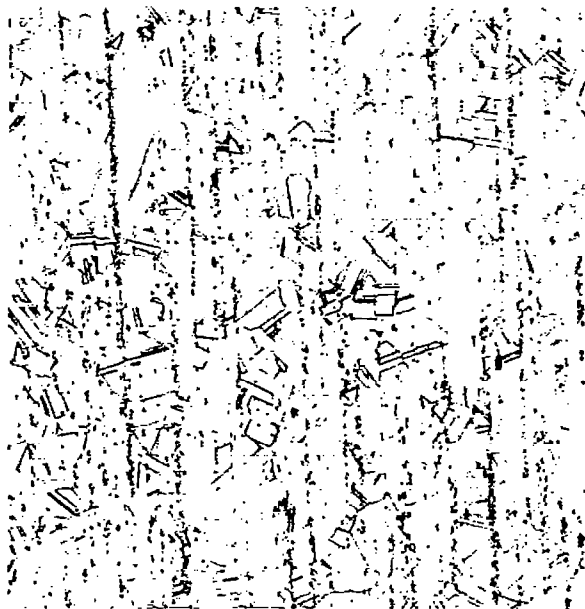
Interior X1000

(d) Heat 30276 - ruptured in 997 hours under 22,000 psi at 1350° F.

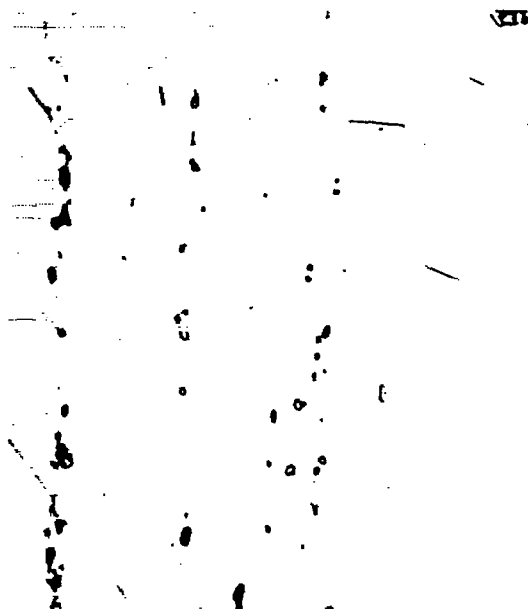
Figure 26.- Concluded.







X100



X1000

(a) Initial.



Fracture X100



Interior X1000

(b) Ruptured in 439 hours under 25,000 psi at 1350° F.



Figure 27.- Initial microstructure and microstructure after rupture testing of low-carbon N-155 alloy bar stock from heat 30276 solution-treated at 2200° F. Electrolytically etched in 10 percent chromic acid. (Treatment: 2200° F, 1 hr, water-quenched.)

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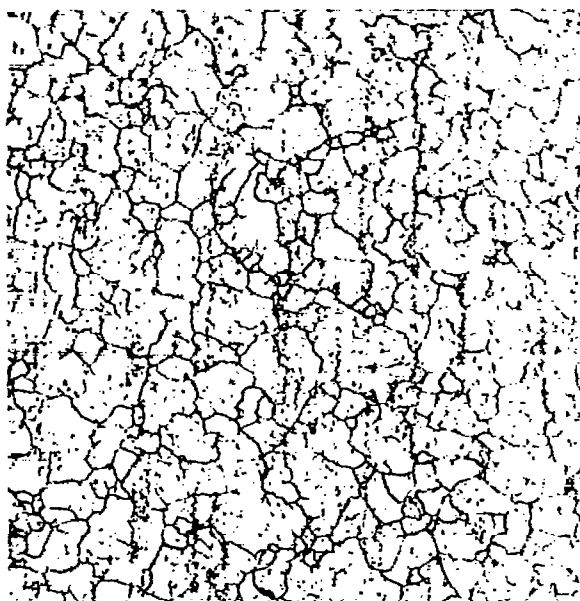
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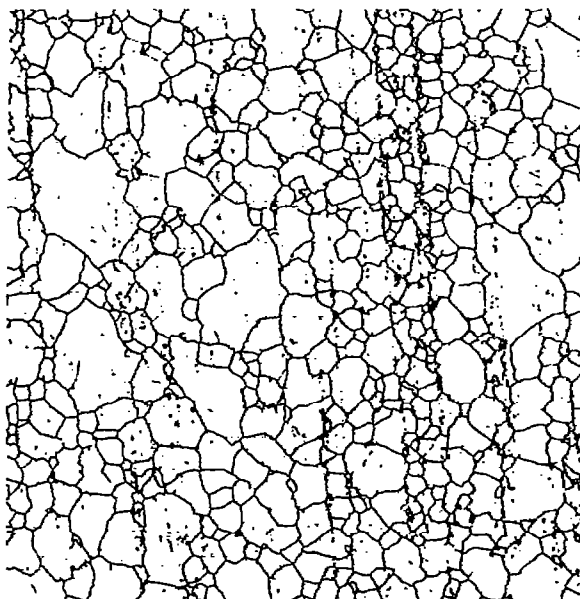


X100

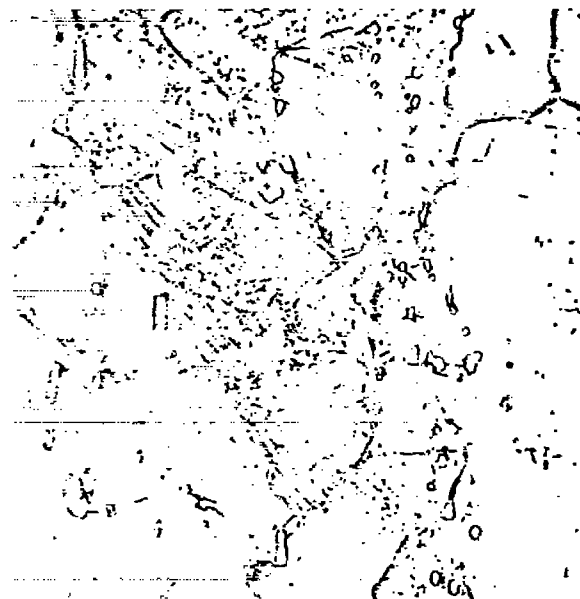


X1000

(a) Heat Al726 - initial.



X100



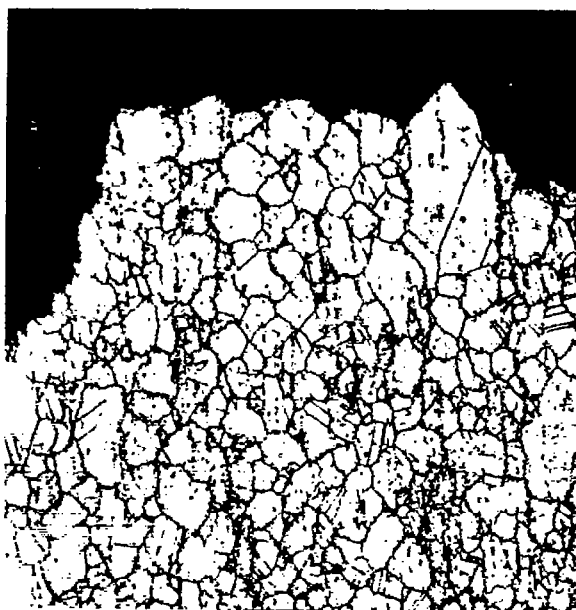
X1000

(b) Heat 30276 - initial.



Figure 28.- Initial microstructures and microstructures after rupture testing of solution-treated and aged low-carbon N-155 alloy bar stock from heats Al726 and 30276. Electrolytically etched in 10 percent chromic acid. (Treatment: 2200° F, 1 hr, water-quenched; 1400° F, 24 hr.)



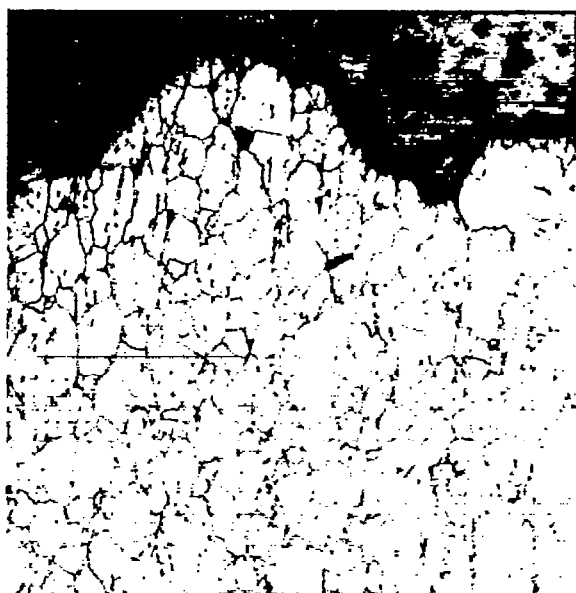


Fracture X100



Interior X1000

(c) Heat Al726 - ruptured in 446 hours under 44,000 psi at 1200° F.



Fracture X100



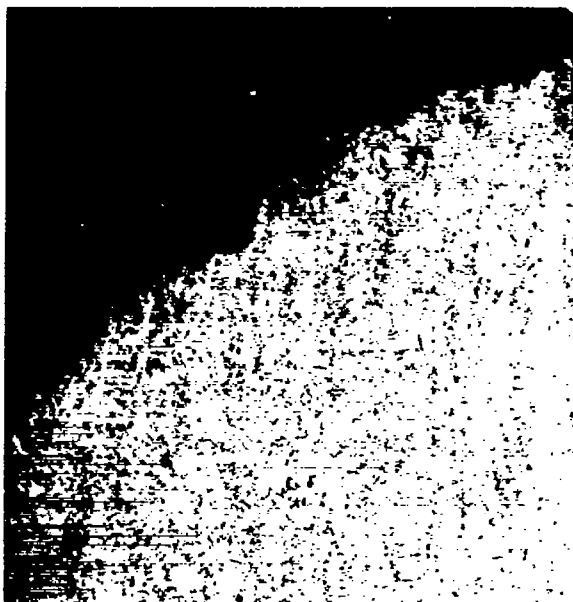
Interior X1000

(d) Heat 30276 - ruptured in 133 hours under 47,000 psi at 1200° F.

Figure 28.- Continued.





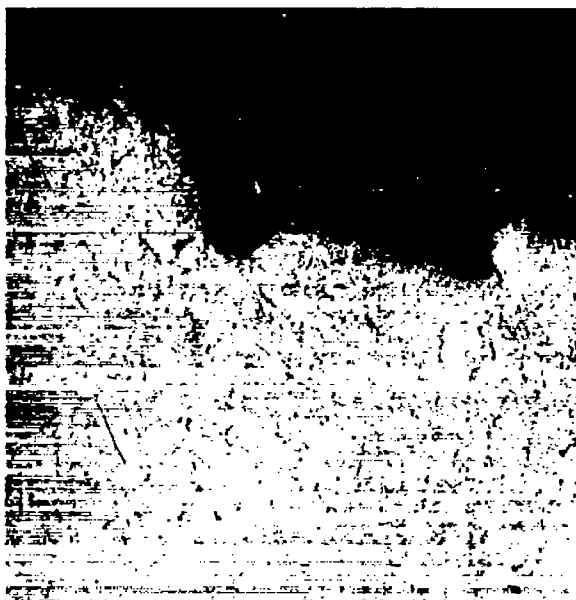


Fracture X100



Interior X1000

(e) Heat A1726 - ruptured in 441 hours under 26,000 psi at 1350° F.



Fracture X100



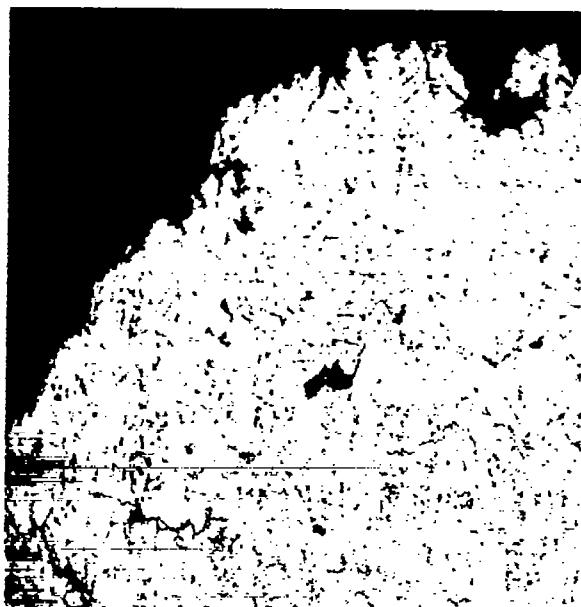
Interior X1000

(f) Heat 30276 - ruptured in 726 hours under 25,000 psi at 1350° F.

Figure 28.- Continued.





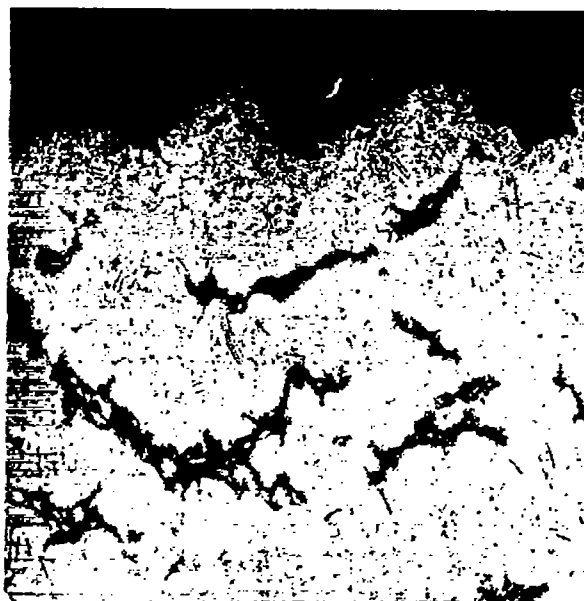


Fracture X100

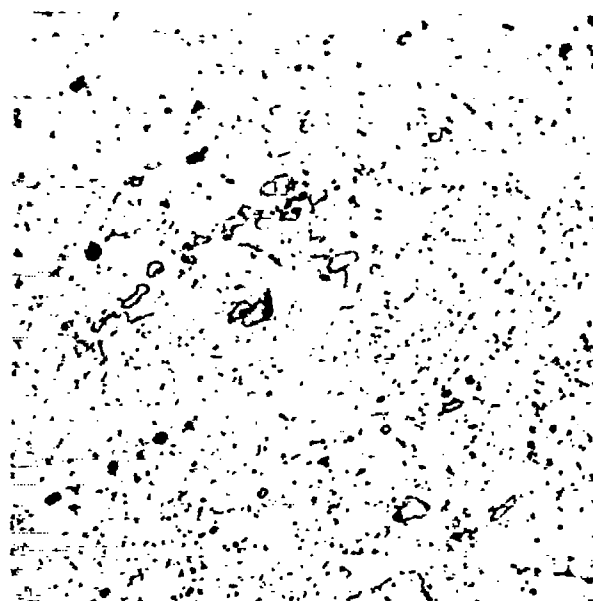


Interior X1000

(g) Heat A1726 - ruptured in 1033 hours under 14,600 psi at 1500° F.



Fracture X100



Interior X1000

(h) Heat 30276 - ruptured in 1131 hours under 14,000 psi at 1500° F.

Figure 28.- Continued.



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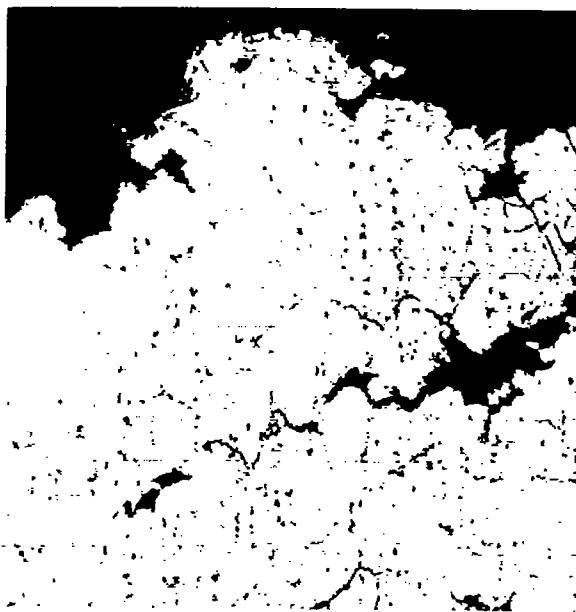
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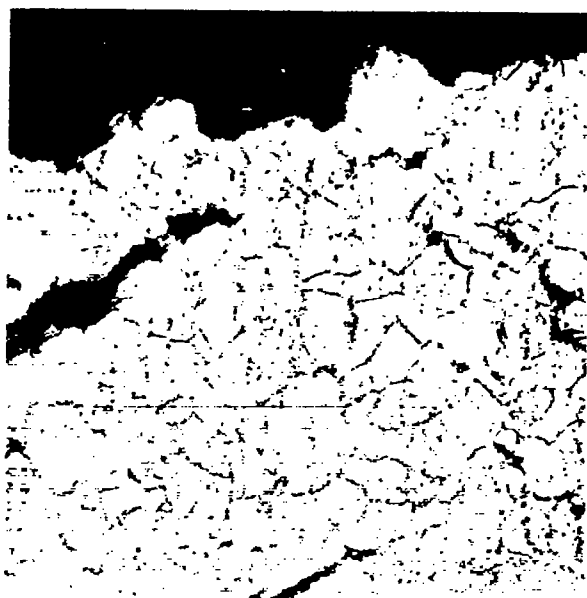


Fracture X100

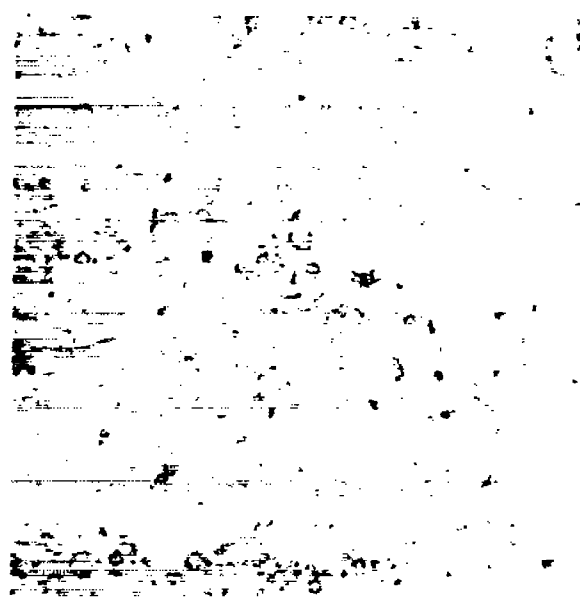


Interior X1000

(i) Heat A1726 - ruptured in 1384 hours under 7400 psi at 1650° F.



Fracture X100



Interior X1000

(j) Heat A1726 - ruptured in 959 hours under 3300 psi at 1800° F.

Figure 28.- Concluded.



